










## Study of the structural characteristics of adsorbents from Navbahar bentonite and their use in the treatment of industrial wastewater

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### ABSTRACT

In order to determine the structure and composition of bentonite samples, X-ray phase, electron microscopic, thermal and spectral analyzes were conducted. Dioctahedral structured montmorillonite reflection  $d_{020} = 0.446$  nm confirms that its layered arrangement contains two octahedral aluminum or magnesium layers separated by a tetrahedral silicon layer. The main sorption activity of the montmorillonite mineral is 54–56 mass% in the B1 clay sample, and about 54–57 mass% in the B2 sample. B1 and B2 clay SEM analysis, nitrogen adsorption isotherms, textural properties and copper (II) and lead (II) adsorption isotherms were obtained. Sample B2 has a larger micro-pore volume and average size compared to sample B1. Determination of lead (Pb) ions by photometry is based on the interaction of inorganic lead compounds with sulfarsazene, which gives the solutions a yellow-orange color. The absorbance is then measured at wavelength  $\lambda = 540$  nm. Research of the composition and structure of primary bentonite clays of alkaline and alkaline earth nature, their textural properties and adsorption activity towards organic and inorganic adsorbates was determined.

**Keywords:** adsorbent, alkaline, clay, Navbahar, bentonite, wastewater.

### INTRODUCTION

In recent decades, the rapid development of industrial production and technological processes has significantly increased the anthropogenic load on natural ecosystems. One of the

most serious environmental problems associated with this process is the contamination of water resources by industrial wastewater containing toxic substances and heavy metals. These pollutants pose a serious threat to ecosystems and human health due to their persistence, toxicity, and

ability to accumulate in living organisms [1,2]. Heavy metals such as copper, lead, cadmium, and zinc are widely used in various industrial sectors including metallurgy, chemical production, mining, electroplating, textile manufacturing, and battery production. As a result, significant quantities of these metals enter natural water bodies through untreated or insufficiently treated wastewater [3].

Unlike many organic pollutants, heavy metals are non-biodegradable and tend to accumulate in aquatic organisms and sediments, causing long-term ecological consequences. The presence of heavy metals in water resources can lead to serious environmental problems such as biodiversity loss, disruption of aquatic ecosystems, and contamination of drinking water sources. Numerous studies have shown that even low concentrations of heavy metals may cause toxic effects in humans and animals, including neurological disorders, kidney damage, and various chronic diseases [4,5]. Therefore, the removal of heavy metal ions from wastewater has become one of the most important environmental protection tasks worldwide. Various physical, chemical, and biological methods have been developed to remove toxic metals from aqueous environments. Among them are chemical precipitation, membrane filtration, ion exchange, electrochemical treatment, and adsorption processes. Although these technologies can be effective, many of them require high operational costs, complex equipment, and significant energy consumption [6]. In addition, some conventional treatment methods generate secondary pollutants, which creates additional environmental problems [7]. For these reasons, researchers are actively searching for alternative methods that are efficient, economical, and environmentally friendly.

Adsorption is considered one of the most promising technologies for wastewater purification due to its simplicity, high efficiency, and relatively low cost. The effectiveness of adsorption processes largely depends on the type and properties of the adsorbent material used [8]. In recent years, natural minerals and low-cost materials have attracted considerable attention as potential adsorbents for removing heavy metals from contaminated water [9]. Among these materials, clay minerals have proven to be particularly effective due to their unique structural and physicochemical properties. Clay minerals are

widely distributed in nature and possess high adsorption capacity, large specific surface area, and significant cation exchange capacity. These characteristics make them suitable for removing various pollutants including heavy metals, dyes, and organic compounds from aqueous solutions [10]. Bentonite, a natural clay primarily composed of the mineral montmorillonite, is considered one of the most promising adsorbent materials for environmental applications. Montmorillonite belongs to the smectite group of clay minerals and is characterized by a layered aluminosilicate structure consisting of two tetrahedral silica sheets surrounding an octahedral alumina sheet [11].

The unique layered structure of montmorillonite allows water molecules and exchangeable cations to enter the interlayer space, resulting in swelling properties and high ion exchange capacity. These characteristics significantly enhance the adsorption performance of bentonite clays, making them suitable for the removal of various contaminants from aqueous media [12]. Furthermore, montmorillonite clays can be modified chemically or thermally to improve their adsorption capacity and selectivity toward specific pollutants [13]. In recent years, numerous studies have been devoted to the development of modified clay-based adsorbents with improved structural and textural characteristics [14]. Chemical activation, acid treatment, and modification with organic or inorganic compounds are widely used methods to enhance the adsorption properties of clay minerals [15]. Such modifications can increase the surface area, pore volume, and number of active adsorption sites on the clay surface, thereby improving their sorption capacity for heavy metal ions and organic pollutants [16].

The adsorption behavior of clay minerals depends on several factors including mineralogical composition, particle size distribution, specific surface area, pore structure, and the presence of exchangeable cations in the crystal lattice. Therefore, a detailed investigation of the structural and physicochemical characteristics of natural clays is essential for evaluating their potential application as adsorbents in environmental technologies [17]. In many countries, including Uzbekistan, significant attention is being paid to the rational use of local mineral resources for the development of environmentally friendly technologies. Uzbekistan

possesses considerable reserves of natural clay minerals, including bentonite deposits that have not yet been fully utilized for industrial and environmental applications [18]. The Navbahar bentonite deposit located in the Navoi region represents one of the most promising sources of natural clay materials with potentially high adsorption capacity.

Previous studies have shown that bentonite clays from this deposit contain a significant amount of montmorillonite and exhibit favorable physicochemical properties for sorption processes [19]. However, comprehensive investigations of their mineralogical composition, structural characteristics, and adsorption properties are still limited. Understanding these properties is essential for determining the potential of Navbahar bentonite as an effective adsorbent for wastewater treatment.

In addition, the development of low-cost sorbents based on locally available natural materials is particularly important for developing countries, where advanced water treatment technologies may not always be economically feasible [20]. Natural bentonite clays represent a promising alternative due to their availability, low cost, chemical stability, and environmental compatibility. Therefore, studying the structural and adsorption characteristics of bentonite clays from the Navbahar deposit is of great scientific and practical importance. Such research contributes not only to the development of new environmentally friendly sorbents but also to the efficient utilization of local mineral resources. The aim of this study is to investigate the mineralogical composition, structural characteristics, textural properties, and adsorption behavior of bentonite clays from the Navbahar deposit. Particular attention is given to evaluating their efficiency in removing heavy metal ions such as copper and lead from aqueous solutions. The obtained results may contribute to the development of effective and economically viable technologies for industrial wastewater treatment.

## MATERIALS

Bentonite clay samples were collected from the Navbahar deposit located in the Navoi region of Uzbekistan. Two types of samples were investigated: alkaline bentonite (B1) and alkaline-earth bentonite (B2). Prior to analysis, the raw clay

samples were cleaned from visible impurities and dried in a laboratory drying oven at  $105 \pm 5$  °C until constant weight was achieved.

## Sample preparation

The dried clay samples were crushed and dispersed in distilled water and allowed to stand for 24 hours to promote swelling and dispersion of clay particles. The suspension was then diluted with distilled water in a ratio of 1:5 (sample:water) and stirred for 20 minutes. After mixing, the upper layer of the suspension (approximately 10 cm) was decanted to remove coarse sand particles and isolate the montmorillonite-rich fraction. The collected suspension was further settled and the sediment containing fine clay particles was separated.

To modify the clay structure and remove impurities, the obtained precipitate was treated with 10% H<sub>2</sub>SO<sub>4</sub> solution (1:1) at 40–50 °C for 2 hours under continuous stirring. The treated suspension was then left to stand for an additional 2 hours, after which the solid phase was separated by centrifugation. The resulting material was washed several times with distilled water and dried at  $105 \pm 5$  °C until complete removal of moisture. The crushed clay was then placed in distilled water and left alone to ferment for 24 hours.

## Mineralogical and structural analysis

The mineralogical composition of the bentonite samples was determined using X-ray diffraction (XRD) and microscopic analysis. XRD analysis was performed using the diffuse reflection method with a spectral resolution of  $1 \text{ cm}^{-1}$  [21].

The morphology and elemental composition of the samples were examined using a scanning electron microscope (SEM) EVO MA10 equipped with an energy-dispersive X-ray spectroscopy (EDS) system for microelemental analysis [22].

## Chemical composition

The chemical composition of the bentonite samples was evaluated based on the oxide content. Both B1 and B2 samples contained SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> as the dominant components, which is typical for bentonite clays. Other oxides detected in both samples included Fe<sub>2</sub>O<sub>3</sub>, FeO, P<sub>2</sub>O<sub>5</sub>, SO<sub>3</sub>, and CO<sub>2</sub>, although their concentrations varied between the two clay types [23,24].

## RESULT AND DISCUSSION

The chemical composition of natural clays determined by the classical chemistry method is represented by the following oxides (Figure 1).

The chemical composition of natural bentonite clay samples is expressed in terms of the major oxide components and presented in weight percent (wt.%). The mineralogical analysis of sample B1 revealed the presence of montmorillonite, which was identified based on characteristic diffraction reflections at 1.781, 1.413, 0.455, 0.169, 0.166, and 0.150 nm.

In particular, the presence of montmorillonite in sample B1 was confirmed by the basal reflection d001 with an interplanar spacing of approximately 1.23 nm, which is typical for the layered structure of montmorillonite minerals. This basal spacing indicates the existence of expandable layers in the clay structure.

Under natural conditions, water molecules can be located within the interlayer spaces of montmorillonite. Therefore, the observed spacing of 1.23 nm likely reflects the presence of interlayer water molecules, which contribute to the swelling properties and adsorption capacity characteristic of montmorillonite clays (Figure 2).

Reflex d001 = 1.47 shows that montmorillonite in sample B2 is represented predominantly by calcium and magnesium forms. The presence of reflection  $d_{020} = 0.446$  nm characterizes the dioctahedral structure of montmorillonite, which confirms its layered geometry with two octahedral layers of aluminum or magnesium separated by a tetrahedral layer of silicon. This structure is typical of montmorillonites, but the reflection d001 = 1.47 nm indicates that additional layers of water molecules or other substances may be present between the layers of the mineral, indicating the presence of calcium and magnesium as interlayer

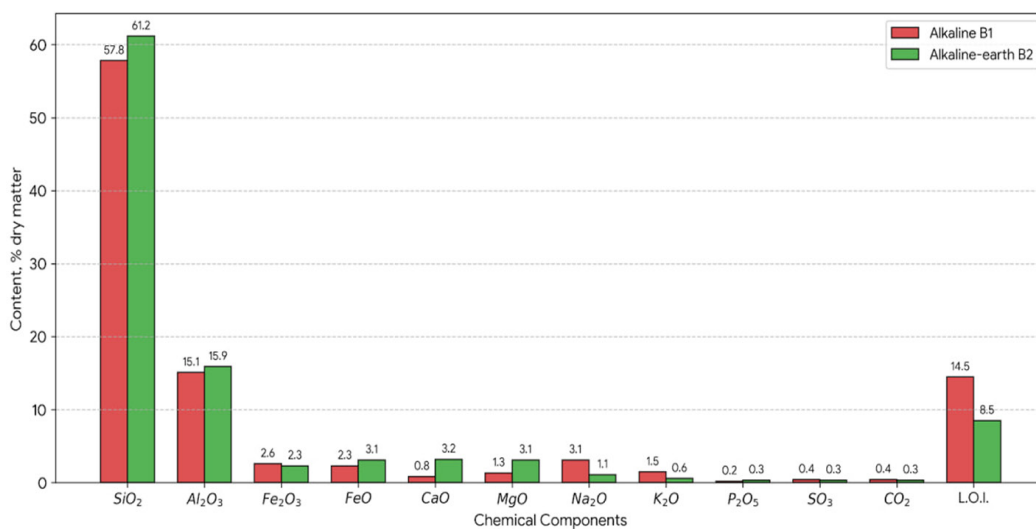


Figure 1. Chemical composition of alkaline (B1) and alkaline-earth (B2) bentonite clays (% dry matter)

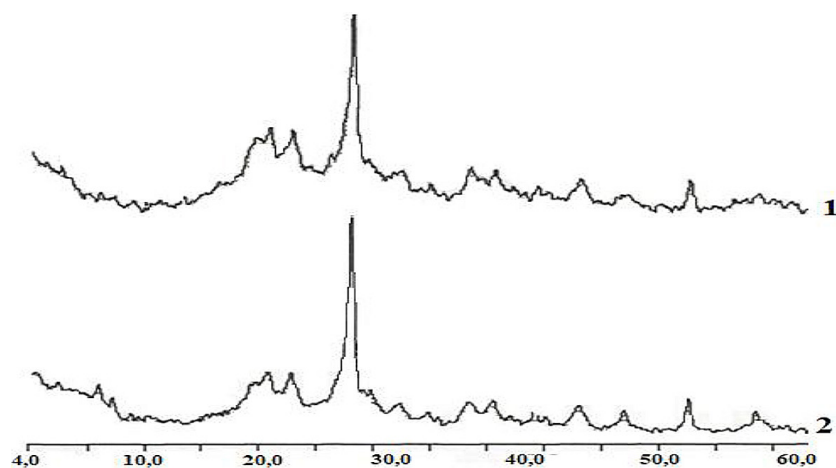
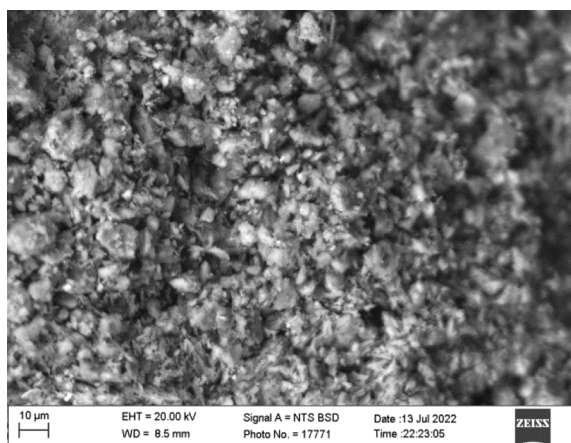
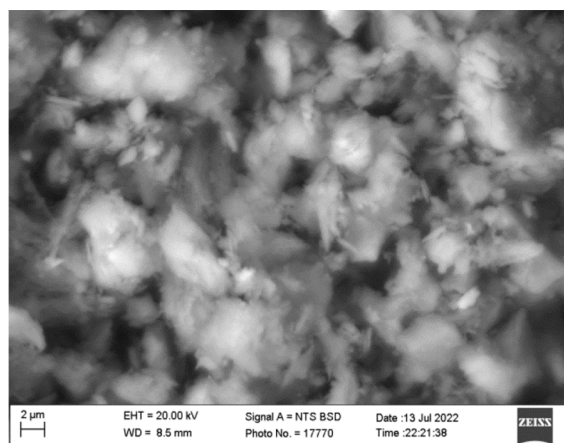


Figure 2. Diffraction patterns of bentonite samples: (1) B1; (2) B2



**Figure 3.** General overview at 10 μm scale B1



**Figure 4.** Detailed microstructure of the particle surface at 2 μm scale B2

cations (Figure 3). Thus, this may indicate increased water absorption capacity and ductility of this particular bentonite compared to sodium montmorillonites (Figure 4).

In microimages of sample B1, montmorillonite is presented mainly in the form of micro- and ultramicroaggregates. In certain areas, large particles were found that were located at a distance from each other and had spike-like endings at the edges. While in sample B2 the characteristic distribution of montmorillonite crystals is different, and they are adjacent to other minerals. Such aggregates usually vary in size from 20 to 80 microns and resemble dried leaves of different densities in shape. Distinct morphological characteristics of montmorillonite crystals correlate with the results of X-ray diffraction and thermal studies (Figure 3 and 4). Energy dispersive analysis of samples B1 and B2 revealed the following sequence of elements: O, Si, Al, Na, Ca and others, and their concentration varies depending on the specific clay sample. The main sorption-active mineral, montmorillonite, is 54–56 wt.% in clay samples for B1 and approximately 54–57 wt.% for B2.

Dispersed composition of natural clays. The determination of the granulometric composition was carried out by several methods. First, the elutriation method with complete

separation of fractions was used. The method is based on the principle of different rates of free sedimentation of solid particles under the influence of gravity in a liquid. In this work, clay fractions with particle sizes less than 100 μm, 1 μm were separated and collected. The content of each fraction in 100 g of clay is determined in wt.%. The results of the granulometric composition are presented in (Table 1).

Based on the presented Table 1, which displays the granulometric composition of clays, the following conclusions can be made: in sample B1, the content of large particles is 31.2%, while for B2 there are more such particles and amount to 39.3%. Therefore, B2 is coarser-grained compared to B1. Samples B1 and B2 have a similar granulometric composition in this range – 28.8% and 29.1%, respectively. B1 contains 8.2% of particles of size  $1 \geq$ , which is significantly more than in sample B2, where such particles are only 3.1%. This indicates that B1 has a higher proportion of ultrafine particles compared to B2.

Considering the purpose of using these bentonites to create adsorbents, particle size distribution can play a key role. Smaller particles usually have higher surface activity due to increased surface area, which can contribute to the efficiency of the adsorption process. However, larger particles may be preferable in terms of mechanical

**Table 1.** Granulometric composition of clays\*, %

Sample	$\geq 100$	$100 \geq 50$	$50 \geq 10$	$10 \geq 5$	$5 \geq 1$	$1 \geq$
B1	31.2	28.8	10.4	1.2	20.2	8.2
B2	39.3	29.1	8.6	0.7	19.2	3.1

**Note:** \*– dimensions are given in μm.

stability of the adsorbent. Thus, sample B1 has a higher content of ultrafine particles, which could potentially make it more active as an adsorbent, but may require additional studies on mechanical stability. Sample B2, being coarser, may offer better mechanical stability, but its adsorption properties may be somewhat reduced due to the smaller surface area of the ultrafine particles (Figure 5).

Subsequent analysis of the particle size distribution was performed by continuous sediment weighing (gravimetric analysis) using a computer program developed in Microsoft Excel. The sedimentation graphs obtained reflect the percentage of particles of different sizes.

Analysis of the particle size distribution was carried out using the method of continuous weighing of sediment. The proportion of large particles ( $\geq 100 \mu\text{m}$ ) is higher in clay B2 compared to B1 (19.5% versus 15.1% in the first method, and 39.3% versus 31.2% in the second). However, according to both methods, the proportion of large particles in clay B2 is higher than in clay B1.

Thus, it can be concluded that B2 clay has a higher content of large and medium-sized particles, while B1 is richer in fine particles. However, both clay samples show slight differences in composition, and the choice between them may depend on the specific application. If a larger surface area for sorption is required, B1 may be preferable due to its higher content of fine particles. In the first method, clay B1 has a higher content of particles sized  $100 \geq 50 \mu\text{m}$  (28.8% versus 29.1% for B2). In the second method, the situation is similar, but the differences are smaller – 28.7% versus 25.3%. For particles sized  $50 \geq 10 \mu\text{m}$ , clay B2 surpasses B1 in both methods (8.6% versus

10.4% in the first and 28.5% versus 20.1% in the second). According to the first method, clay B2 has a lower proportion of particles sized  $10 \geq 5 \mu\text{m}$  (0.7% versus 1.2% for B1). According to the second method, the difference is even greater – 1.8% versus 3.5%. For particles sized  $5 \geq 1 \mu\text{m}$ , clay B2 also shows a lower content according to both methods (19.2% versus 20.2% according to the first and 20.5% versus 22.3% according to the second). However, in the finest fraction ( $1 \geq \mu\text{m}$ ), clay B2 has a lower particle content compared to B1 in both methods (3.1% versus 8.2% according to the first and 4.4% versus 9.3% according to the second). Clay B1 has a larger cation exchange complex (80.6 mEq/100 g) compared to clay B2 (65.5 mEq/100 g). This may indicate that clay B1 contains more layered minerals with cation-exchange properties.

Using nitrogen adsorption, parameters such as total porosity, pore size and distribution were determined, which will allow us to evaluate their adsorption activity. The obtained isotherms are shown in Figure 6. The obtained isotherms were characterized by the corresponding adsorption equations; the data obtained are given in (Table 2).

Based on the data presented in Table 2, we can conclude that the specific surface area of the materials ( $S^1$  and  $S^2$ ) differs between samples B1 and B2. Sample B1 has a large specific surface area according to both measurement methods, which indicates a higher activity of its surface for the adsorption of various substances.

Micropore volume and average micropore size ( $V_a$  and  $D^{**}$ ) also differ between samples. Sample B2 has a larger volume of micropores and an average size of micropores compared to

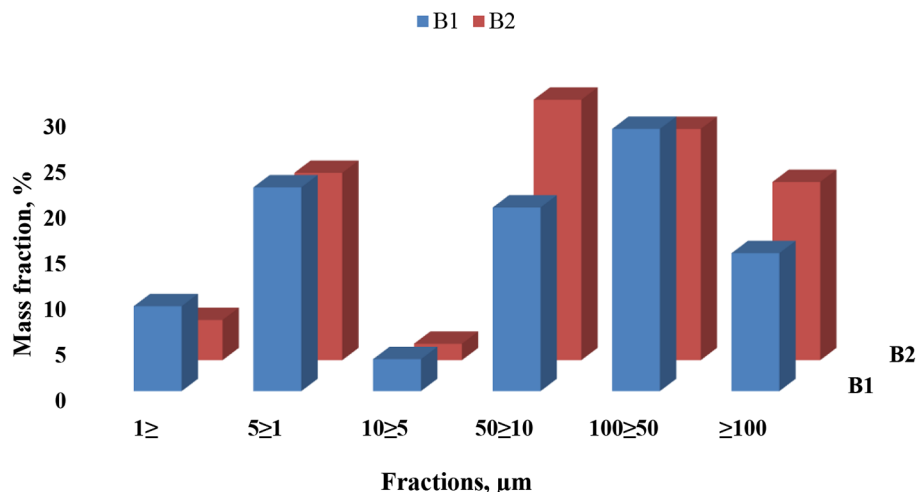


Figure 5. Granulometric composition of clays using the elutriation method

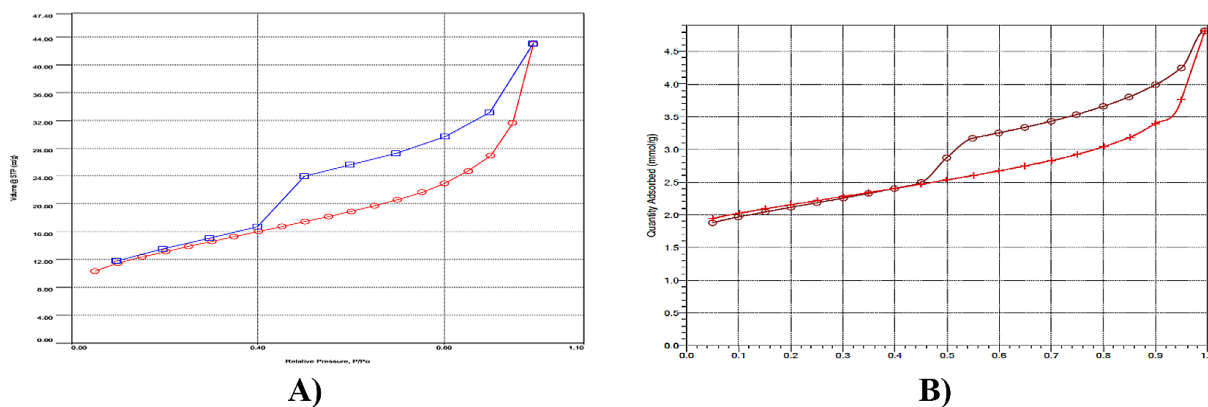


Figure 6. Nitrogen adsorption isotherms on: A) B1; C) B2

Table 2. Textural characteristics of bentonites

Sample	S <sup>1</sup> , m <sup>2</sup> /g	S <sup>2</sup> , m <sup>2</sup> /g	V <sub>a</sub> , sm <sup>3</sup> /g	V <sub>b</sub> , sm <sup>3</sup> /g	R, Å	D <sup>**</sup> , Å	D <sup>***</sup> , Å
B1	56.3	65.4	0.089	0.101	41.48	16.36	6.51
B2	42.7	62.5	0.071	0.082	45.65	18.44	8.43

Note: 1 – specific surface according to BET; 2 – Langmuir specific surface area; \*\* – width of the middle pore; \*\*\* – average micropore size; R – average pore size.

sample B1. These parameters may be important for various adsorption and catalytic processes.

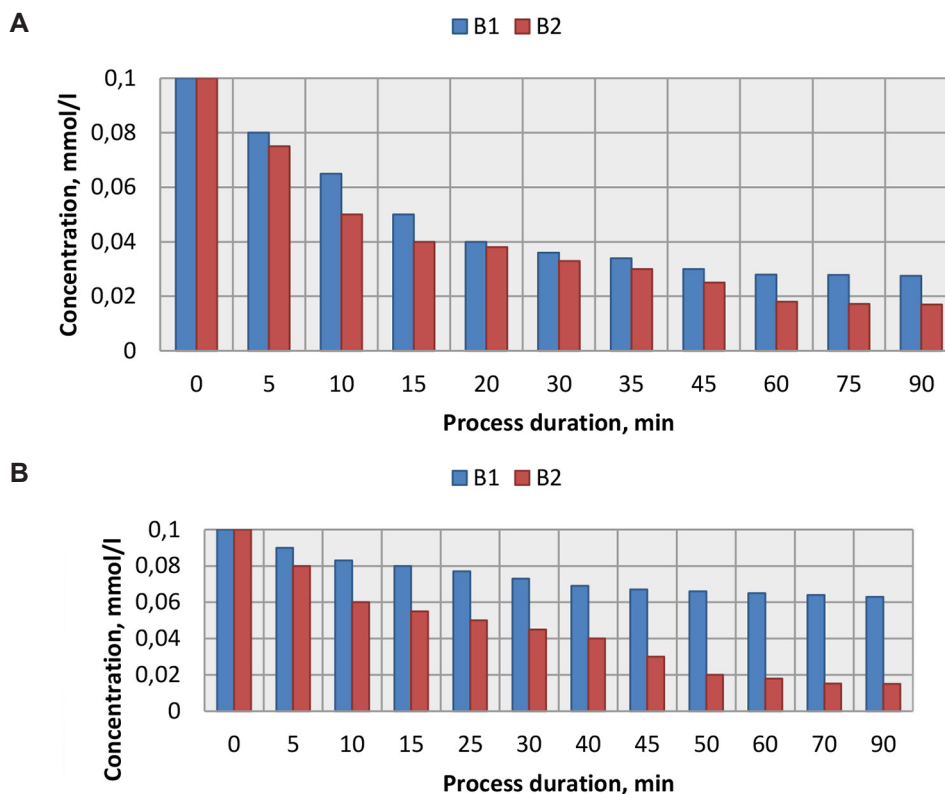
The average pore size (R) also differs between samples, with sample B2 having a larger average pore size. This parameter can affect the permeability and diffusion of substances in the porous structure of the material. Thus, these textural characteristics indicate differences in the structure and properties of samples B1 and B2, which may be key when choosing a material for specific technological and scientific tasks.

Further studies of adsorption characteristics were carried out using aqueous solutions of heavy metal salts, because CuSO<sub>4</sub> and Pb(NO<sub>3</sub>)<sub>4</sub>. Determination of copper ions (Cu) using photometry is based on the formation of a copper complex with sodium diethyldithiocarbamate ((C<sub>2</sub>H<sub>5</sub>)<sub>2</sub>NCS<sub>2</sub>Na) in slightly acidic and ammonia solutions, which gives them a brown color. The absorbance is then measured at wavelength X = 430 nm. To determine the concentration of copper (II) in a sample, a calibration graph is used, based on the optical density for various copper concentrations (from several mmol/l to 1 mmol/L) in standard working solutions.

Similarly, the determination of lead ions by photometry is based on the interaction of inorganic lead compounds with sulfarsazene, which gives the solutions a yellow-orange color. The absorbance is then measured at wavelength X = 540 nm.

CuSO<sub>4</sub> and Pb(NO<sub>3</sub>)<sub>4</sub> were used to prepare model solutions with an initial concentration of metal ions of 0.1 mmol/l and a ratio of 0.01 g of clay per 50 ml of solution. The process of purifying model solutions from heavy metal ions can be seen in the (Figure 7).

According to the kinetic curves, the maximum sorption rate is observed at the first stage of the purification process. For example, for adsorbent B2, the sorption rates of Cu<sup>2+</sup> and Pb<sup>2+</sup> ions in the first five minutes are 1.0110<sup>-2</sup> and 0.8910<sup>-2</sup> mmol/l\*min, respectively, and for adsorbent B1 – 1.1210<sup>-2</sup> and 0.8110<sup>-2</sup> mmol/l\*min. The high initial adsorption rate can be explained by the presence of electrostatic interactions between metal cations and the negatively charged surface of bentonites. As time passes, cations continue to migrate from the bulk solution through the boundary layer of aluminosilicate particles, where their subsequent adsorption occurs. The whole process can be divided into two stages: the first is the active phase of adsorption and the second is a more moderate phase, during which adsorption equilibrium is achieved. The first phase is characterized by the diffusion of cations to the surface of the sorbent and their subsequent adsorption, while the second phase is associated with the diffusion of cations to active sites inside the sorbent. The adsorption efficiency of each ion is determined by the nature and concentration of active sites on the surface.



**Figure 7.** Dynamics of decrease in the concentration of heavy metal ions: (A)  $\text{Cu}^{2+}$ ; (B)  $\text{Pb}^{2+}$

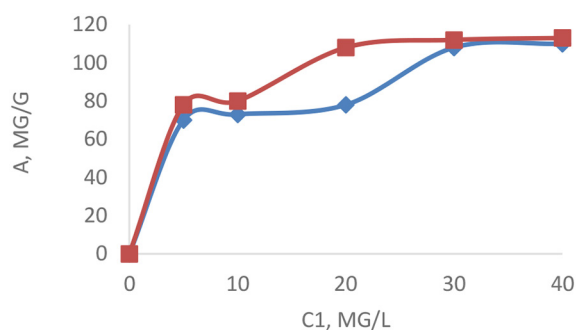
It is interesting to note that the time required to reach equilibrium can vary even for samples of the same type.

Sample B1 has a higher specific surface area and smaller pores, which may make it more effective for certain applications, such as adsorption and catalysis. Sample B2, on the other hand, has larger pores and could perhaps be preferred for other applications where greater flow is required. In the process of adsorption of heavy metal ions when using natural clays, cations are released from the exchange nodes of the crystal structure of montmorillonite, which indicates the exchange of these cations for metal ions from solutions.

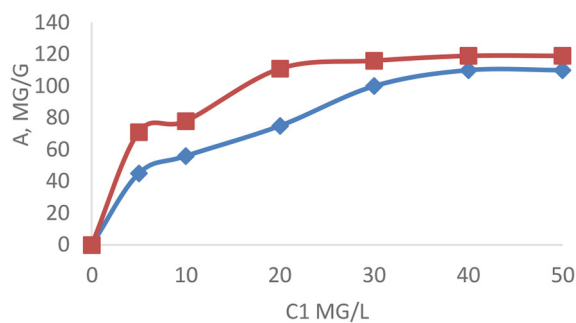
In Figures 8 and 9 illustrate the removal capacity of copper (II) and lead (II) on the studied bentonites (process conditions:  $T=25\pm 1$  °C,  $\text{pH}=7$ ). It should be noted that at  $\text{pH}=7$ , the reduction in lead (II) concentration is attributed to a combined process of surface adsorption and chemical precipitation as lead hydroxide,  $\text{Pb}(\text{OH})_2$ .

As can be seen from the adsorption isotherm, B1 is characterized by higher values of the amount of adsorption  $A$  (mg/g) and its value is 111 and 120 mg/l, respectively, in relation to  $\text{Pb}^{2+}$  and  $\text{Cu}^{2+}$  at an equilibrium concentration of 40 mg/l. For B1, the adsorption isotherms demonstrate a pronounced step profile, in contrast to

B2, where a more uniform increase in concentration is observed with increasing values of the equilibrium concentration on the abscissa. The chemical composition of natural bentonite clay samples is presented in weight percent (wt.%). The mineralogical analysis of sample B1 revealed the presence of montmorillonite, identified by characteristic diffraction reflections. According to previous studies on smectite minerals, this spacing is highly sensitive to the nature of the interlayer cations and the degree of hydration [25]. Water molecules located within the interlayer spaces contribute to the swelling properties characteristic of montmorillonite clays. The stabilization of the adsorption curve suggests that the adsorption process is approaching equilibrium and that most of the available adsorption sites on the bentonite surface have been occupied. In sample B1, montmorillonite appears as micro-aggregates with spike-like endings, whereas in B2, the crystals resemble dried leaves in morphology. Such structural variations are fundamentally linked to the specific crystallization environment and the surface free energy of the clay particles [26]. The elemental composition confirmed by energy dispersive X-ray analysis (EDX) showed a sequence of O, Si, Al, Na, and Ca, which is characteristic of the standard aluminosilicate



**Figure 8.** Pb<sup>2+</sup> adsorption isotherms on B1 (blue) and B2 (red)



**Figure 9.** Cu<sup>2+</sup> adsorption isotherms on (blue) and B2 (red)

framework of bentonites [27]. The adsorption kinetics revealed that the maximum sorption rate occurs within the initial five minutes of the process. This rapid initial uptake is primarily driven by strong electrostatic interactions between the metal cations (Cu<sup>2+</sup> and Pb<sup>2+</sup>) and the negatively charged surface sites of the bentonite. This phase is subsequently followed by a slower intra-particle diffusion phase, which is a well-established kinetic model for porous aluminosilicates [28]. The role of pH in metal speciation is critical for understanding the removal mechanism. At a neutral pH of 7.0, the solubility limit of lead is typically exceeded, leading to the formation of lead hydroxide precipitates [Pb(OH)<sub>2</sub>], which are then effectively captured by the clay matrix. This dual mechanism combining surface adsorption and chemical precipitation explains the significantly higher removal capacity observed for lead compared to copper [29]. The saturation behavior observed at higher concentrations is consistent with classical adsorption isotherm models reported for clay-based sorbents [30]. The enhanced performance of the Navbahar bentonites is attributed to their unique structural characteristics: the presence of expandable montmorillonite layers, a high specific surface area, and active surface functional groups, particularly hydroxyl (–OH) groups. These features facilitate multiple removal pathways, including ion exchange, surface complexation, and mechanical entrapment of precipitates, making these clays highly effective for industrial wastewater remediation [31]. The observed adsorption performance can be attributed to the structural characteristics of bentonite, particularly the presence of montmorillonite layers, surface hydroxyl groups, and exchangeable cations that facilitate ion exchange and surface complexation mechanisms. These properties

enable bentonite to effectively remove contaminants from aqueous solutions.

## CONCLUSIONS

The results of this study confirmed that bentonite clays from the Navbahar deposit are mainly composed of montmorillonite and exhibit significant adsorption potential. Mineralogical and microscopic analyses revealed differences in the structural characteristics of samples B1 and B2, particularly in particle size distribution and cation composition. Sample B1 is dominated by Na<sup>+</sup> cations and contains a higher proportion of fine particles, which contributes to its larger specific surface area and higher adsorption capacity. In contrast, sample B2 contains predominantly Ca<sup>2+</sup> cations and is characterized by larger particle sizes and greater micropore volume.

The adsorption experiments demonstrated that both clay samples are effective sorbents for the removal of heavy metal ions such as Cu<sup>2+</sup> and Pb<sup>2+</sup> from aqueous solutions, although B1 exhibited higher adsorption efficiency during the initial stage of the process. Overall, the obtained results indicate that Navbahar bentonite clays can be considered promising low-cost adsorbents for wastewater purification and environmental remediation applications.

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