

Research Article

Characterization Analysis of Mudstone and Study of Its Pb (II) Adsorption Characteristics in Polluted Water Bodies

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In order to explore a medium material for the efficient treatment of Pb(II) pollutants in groundwater, in this paper, mudstone is selected as the medium material, and the morphological structure of the mudstone is characterizes via X-ray diffraction (XRD), scanning electron microscopy (SEM), and Brunauer–Emmett–Teller (BET) analyses to study the feasibility of the mudstone adsorbing Pb(II) ions. Then, static adsorption experiments are carried out to investigate the removal effect of mudstone on Pb(II) in aqueous solutions under different conditions and to determine the optimal adsorption conditions. Finally, the results are fitted and analyzed using a thermodynamic model to explore the adsorption mechanism of the mudstone. The main results of this study are as follows. The main mineral composition of the mudstone used in the experiments includes CaCO₃, SiO₂, CaAl₂O₄·10H₂O, and CaFe₄O₇. The specific surface area of the mudstone is as high as $23.027 \text{ m}^2 \cdot \text{g}^{-1}$, the pore size is 9.145 nm, and its surface structure is rough, with pores and fissures developed. The pore space and adsorption capacity of the mudstone were enhanced. When 1 g-L^{-1} of mudstone was added, the pH value of the solution was 6, the reaction time was 60 min, and the initial concentration of Pb(II) was 30 mg-L^{-1} . The removal efficiency of Pb reached 84.5%, and the adsorption amount was 25.352 mg-g^{-1} . For the removal of Pb(II) from the aqueous solution by the mudstone under different concentrations of Pb(II), the reaction was in accordance with the Langmuir adsorption isotherm model, and the maximum adsorption amount reached 54.975 mg-g^{-1} . The relationship between the removal of Pb(II) and the reaction time was in accordance with the pseudo-second-order rate model. The results of this study suggest that mudstone can be used for the removal of Pb(II) from aqueous media.

1. Introduction

Water is an indispensable natural resource in human life and is an integral part of the ecological and environmental system [1]. Currently, due to the rapid development of agriculture and industry, the excessive use of chemical fertilizers and pesticides in the agricultural field has caused serious pollution of water bodies with Pb(II) ions [2, 3]. Pb(II) ions in water bodies are difficult to degrade, and they have a high toxicity. Long-term consumption of water with a high lead content is likely to cause cancer. The lead pollution cycle is long, and it is easily bioaccumulated. Through its gradual accumulation in the food chain, it causes serious harm to the human living environment, biosphere, and human health [4–7]. Therefore, the purification of polluted water bodies has become a research hotspot in the field of environmental science, and it is of great significance to apply clay mineral materials to the study of the adsorption of heavy metals in water bodies [8, 9]. There are two treatment methods for water bodies polluted by Pb(II) ions: one is to reduce the bioavailability of the Pb(II) ions in the water body, and the other is to directly remove the Pb(II) ions from the water body [10, 11]. Therefore, some efficient water treatment technologies, for example, physical adsorption, electrochemical adsorption, ion exchange, chemical precipitation, and a series of other treatment methods and technologies, are used in the treatment of Pb(II) in water bodies [12].

In the method of absorbing Pb(II), the choice of the adsorbent is extremely important. Clay minerals have a super-self-purification capacity in the restoration of water bodies polluted by Pb(II) ions [13]. The common clay minerals used to restore water bodies heavily polluted by Pb(II) ions include montmorillonite, attapulgite, zeolite, kaolinite, sepiolite, vermiculite, and illite [14-17]. As a mineral material with abundant reserves and a low price, mudstone is a composite clay mineral material composed of layered porous silicate-rich minerals. Mudstone is mainly composed of minerals such as illite, kaolinite, montmorillonite, quartz, feldspar, mica, epidote, chlorite, ferromanganese oxide, and organic matter [18]. There are certain differences in the mineral components contained in different regions [19]. Mudstone has a strong viscoelasticity, is easily weathered into fine particles, is easy to crush, easy to mine, cheap, and easy to obtain. In addition, as a composite clay mineral material, mudstone is a good soil-forming parent material, and its basic characteristics determine that it will not generate secondary pollution when used as an adsorbent. In addition, the restoration cost of this method is low, it is simple and easy to operate, and it has broad application prospects.

In this study, the adsorption method was used to remove the Pb(II) in a water body. The aim was to develop an environmentally friendly adsorption material with a high adsorption efficiency, good performance, and no secondary pollution. Therefore, in this study, through the characterization analysis of mudstone, the possibility of its adsorption of the heavy metal Pb(II) was explored, and the adsorption effect of the mudstone on Pb(II) in a water body under different influencing factors was investigated so as to provide a theoretical scientific basis and technical support for the efficient use of mudstone material.

2. Materials and Methods

2.1. Materials. The mudstone used in this study was collected from Yaoqu Village, Yaoqu Town, Yaozhou District, Tongchuan City, Shaanxi Province, and the chemical agent used was purchased from the Aladdin Reagent Co., Ltd. (Shanghai, China).

2.2. Preparation of Mudstone Material. First, the mudstone protolith collected was air dried, and the air-dried clay mineral material mudstone was refined. Then, the refined mudstone was cleaned with deionized water for three times to remove the impurities in the sample. The washed sample

was air dried again and sieved through a 100-mesh screen to make the mudstone material required for the experiment. The prepared mudstone material was placed in a plastic bag and stored under dry conditions for later use. The basic physical and chemical properties of the mudstone material are presented in Table 1. The Pb content of the mudstone was far lower than the soil pollution risk screening value, and it did not carry the target heavy metal when adsorbing the Pb(II) in the polluted water body.

2.3. Characterization of Mudstone. The surface morphology and elements composition of the mudstone were analyzed using X-ray diffractometers (America -FEI-Quanta FEG 250 and Japan-Rigaku-Smart Lab 9KW models), and the specific surface area and pore size of the mudstone were determined using an America - Mack -ASAP 2020HD8.

2.4. Adsorption Experiment. A batch experiment was conducted to study the adsorption effect of the mudstone on Pb(II) in 100 mL of water contaminated with Pb(II) at a concentration of 30 mg·L⁻¹, Experiment 1: Different amounts of mudstone $(0.25 \text{ g} \cdot \text{L}^{-1}, 0.5 \text{ g} \cdot \text{L}^{-1}, 0.75 \text{ g} \cdot \text{L}^{-1})$ $1\,g{\cdot}L^{-1},\ 1.25\,g{\cdot}L^{-1},\ and\ 1.5\,g{\cdot}L^{-1})$ were added to the contaminated water under constant temperature shaking. Experiment 2: The best adsorption amount of mudstone from experiment 1 was added to the polluted water, the pH of the solution was adjusted (2, 3, 4, 5, 6, 7, and 8), and the reaction time was 120 min. Adsorption experiments were conducted to determine the best pH value for heavy metal adsorption by the mudstone. Experiment 3: The best adsorption amount of mudstone from experiment 1 was added, and the pH was adjusted to the ideal value obtained from experiment 2. Then, experiments on Pb(II) adsorption by the mudstone were conducted to study the effect of the adsorption reaction time on the adsorption effect by collecting samples at different times (5 min, 10 min, 20 min, 30 min, 40 min, 50 min, 60 min, 70 min, 80 min, 90 min, 100 min); Experiment 4: Under the optimal conditions determined in Experiment 1, Experiment 2, and Experiment 3, mudstone was add to solutions with various initial Pb(II) concentration (10, 20, 30, 40, 50, and $60 \text{ mg} \cdot \text{L}^{-1}$) to observe the Pb(II) adsorption effect of the mudstone under different initial concentrations. The supernatant of the adsorbed mixture was filtered, and the Pb(II) concentrations of the filtrate was determined via multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS). To ensure the accuracy of the experiments, each experiment was repeated three times.

The removal rate and adsorption amount are important indicators of the performance of adsorbent materials. The adsorption amount (q_e) and removal rate (R) of lead by the mudstone were calculated as follows:

$$q_e = \frac{(C_0 - C_e)}{m} \times V,$$

$$R = \frac{C_0 - C_e}{C_0} \times 100\%,$$
(1)

TABLE 1: Basic physical and chemical properties of the mudstone.

Material	рН	Conductivity (mS·m ⁻¹)	Particle size composition (%)		Ph content	Cation exchange capacity		
			Clay particle	Powder particle	Sand	(mg·kg ⁻¹)	(mmol·kg ⁻¹)	Expansion rate (%)
Mudstone	8.29	14.8	16.33	83.40	0.27	0.322	101.44	25.36

where q_e is the unit adsorption capacity of the composite clay mineral material for Pb (II) after adsorption equilibrium (mg·L⁻¹); C_0 is the initial concentration of Pb(II) (mg·L⁻¹); C_e is the concentration of Pb(II) in the adsorption equilibrium state (mg·L⁻¹); V is the volume of the sewage solution poured into the conical bottle initially (mL); m is the amount of mudstone used (g) [20].

3. Results and Discussion

3.1. Characterization Analysis of Mudstone. The scanning electron microscopy (SEM) morphology results for the mudstone are shown in Figures 1(a)-1(d). Figures 1(a)-1(d)present SEM photos of the mudstone collected from the Tongchuan area, Shaanxi, under magnifications of 5000x, 10000x, 20000x, and 50000x, respectively. It can be seen from Figure 1 that the surface structure of the mudstone is rough and consists of aggregates of irregular flakes; the particles are connected by irregular surface-to-surface and surface-to-edge contacts; and the pore channels of the mudstone are unobstructed. This scattered structure helps in the generation of pores, interstices, voids, cracks, fissures, and the connections between them. The pores, interstices, voids, cracks, and fissures are mostly formed via stacking of the irregular mineral particles contained in the mudstone, so there is a certain difference in the pore size and pore wall thickness. The size of the space between the pores also varies, which not only increases the free adsorption group of the mudstone but also helps the mudstone to form a pore channel structure. There are pores and fissure structures of different sizes distributed on the surfaces of the mudstone particles, which are aggregated in a disorderly manner. The well-developed pores and rough pore walls on the mudstone surface and the good connection between the pores enhance the effective space and adsorption capacity of the mudstone pore channels and improve the physical adsorption and chemisorption capacity of the mudstone.

Phase analysis of the mudstone material was carried out. The X-ray diffraction (XRD) results for the mudstone are shown in Figure 2. The results show that the minerals contained in mudstone mainly include CaCO₃, SiO₂, CaAl₂O₄•10H₂O, and CaFe₄O₇. This is because clay minerals are the main rock forming minerals in mudstone, and the clay minerals are mainly aluminum-silicate minerals. Therefore, the Si and Al contents of the mudstone are large. In addition, the shapes and positions of all of the main diffraction peaks of the crystals are sharp and symmetrical, and the crystal structure is complete. The strong binding capacity of the silicate minerals contained in the mudstone for Pb (II) can be used to improve the adsorption capacity of the mudstone for the heavy metal Pb (II) to a large extent. Figure 3 shows the nitrogen adsorption curve of the mudstone. Based on analysis of the nitrogen adsorption curve, the adsorption isotherm belongs to the second category of the Brunauer-Emmett-Teller (BET) classification, with a small slope and slow rise in the first half and a sharp rise in the second half. As the relative pressure increases, capillary condensation occurs simultaneously with multilayer adsorption. When $P/P_0 = 0$, the curve intersects with the ordinate (representing the adsorption volume) at a nonzero value, the intercepts are not equal, so there are micropores and the micropore volumes are not equal. The average specific surface area obtained using methods such as the BET method is 23.027 m²·g⁻¹, and the average pore size is 9.145 nm.

3.2. Adsorption of Pb(II) Ions in Batch Systems. The Pb(II) adsorption performance of the mudstone is not only related to its surface structure but is also influenced by external factors. Mudstone was used as the adsorption material to investigate the effects of the pH, amount of mudstone addition, reaction time, and initial Pb(II) concentration of solution on the heavy metal ion adsorption performance of the mudstone.

3.2.1. Effect of Mudstone Dosage on Absorption Effect. The results of the effect of the mudstone dosage on the removal of Pb(II) are shown in Figure 4. This is mainly due to the fact that the Pb(II) concentration of the solution was fixed, and the removal efficiency of Pb(II) increased gradually as the amount of mudstone increased, which caused the mudstone to reach adsorption equilibrium. The removal efficiency increased linearly as the amount of mudstone added increased from $0.25 \text{ g} \cdot \text{L}^{-1}$ to $1 \text{ g} \cdot \text{L}^{-1}$. The Pb(II) removal efficiency of the mudstone was as high as 85% when the amount of mudstone was $1 \text{ g} \cdot \text{L}^{-1}$, and it had reached the equilibrium at this time. Although the Pb(II) adsorption efficiency of the mudstone exhibited a tendency toward equilibrium with increasing mudstone dosage, when the addition of mudstone was small, the specific surface area and the number of adsorption sites on the mudstone were limited, and the adsorption sites were fully utilized, thus reaching adsorption saturation quickly and resulting in a high adsorption amount. However, the limited number of adsorption sites was not sufficient to adsorb a large amount of the Pb(II) in the solution, so the removal efficiency was low [21]. As the addition of mudstone gradually increased, the specific surface area and the number of adsorption sites and functional groups of the mudstone also increased, which caused the Pb(II) content of the solution to decrease. However, this led to an excess of adsorption sites on the surface of the mudstone, and the phenomenon of



FIGURE 1: SEM photos of mudstone.



FIGURE 2: Mudstone X-ray diffraction analysis.

unsaturated utilization of the adsorption sites occurred. Based on the analysis of the results presented in Figure 5, the optimum amount of mudstone addition was $1 \text{ g} \cdot \text{L}^{-1}$ for Pb(II) adsorption by mudstone.

3.2.2. Effect of Solution pH on the Adsorption Effect. According to the above effect of the amount of mudstone addition on the Pb(II) adsorption effect of the mudstone, the amount of mudstone was set as $1 \text{ g} \cdot \text{L}^{-1}$ in the experiment conducted to determine the effect of the solution pH on the

adsorption effect. The removal efficiencies were all very low at pH < 3, and the removal efficiencies were significantly higher at $pH = 3 \sim 6$. At $pH = 6 \sim 8$, the curve leveled off and the removal efficiency stabilized near the maximum value, and the removal efficiency was above 85%. Therefore, mudstone is most suitable for Pb(II) removal under weakly acidic or neutral conditions. At pH 6-7, Pb(II) may combine with OH⁻ to produce Pb(OH)⁺ and Pb(OH)₂ complexes via precipitation, which reduces the unfavorable contact with the oxidized surface [22]. For pH 6-7, the increase in the removal of Pb(II) by the mudstone was the result of the combined effect of physical adsorption and a chemical precipitation reaction; the adsorption amount reached the maximum value, and the adsorption effect gradually stabilized [23]. The mudstone contained Fe and Al oxides with variable charges, and as the pH increased, the variable negative charge in the solution increased, causing the gravitational force on the Pb(II) increase and the electrostatic adsorption of Pb(II) increase. The pH of the solution not only affects the magnitude of the electricity charge on the surface of the clay mineral material and the activity of the adsorption sites, but also the form of the metal ions present in the solution, thus affecting its adsorption properties [24]. Therefore, pH=6 was determined to be the optimum pH value for Pb(II) adsorption on mudstone.

3.2.3. Effect of Reaction Time on the Adsorption Effect. Based on the effects of the amount of mudstone addition and the pH of the solution on the adsorption effect, the optimum



FIGURE 3: Nitrogen adsorption curve of mudstone.



FIGURE 4: Effect of mudstone dosage on the removal of Pb(II).

amount of mudstone addition and solution pH were set as 1 g-L^{-1} and pH = 6, respectively, in the next set of adsorption experiments. As shown in Figure 6, the adsorption rate of Pb(II) by mudstone was fast, the Pb(II) concentration of the solution decreased rapidly, and the removal efficiency increased. The Pb(II) removal efficiency of the mudstone was nearly 25% in 0–20 min, and the adsorption capacity was nearly 23 mg·g⁻¹. At 60 min, the Pb(II) removal efficiency of the mudstone reached 89%, its Pb(II) adsorption capacity reached 26.7 mg·g⁻¹, and both the removal efficiency and

adsorption capacity reached the maximum values. During the reaction, the removal efficiency and adsorption amount did not change significantly as the reaction time increased, and they reached an equilibrium state, indicating that the adsorption of Pb(II) by the mudstone was characterized by rapid adsorption and dynamic equilibrium, which is generally stable and will not be resolved [25]. In summary, in the experiment on the static adsorption of Pb(II) by mudstone, the adsorption time was set to 60 min. The rapid adsorption characteristics enable the mudstone to give full play to the



FIGURE 5: Effect of pH on the removal of Pb(II) by mudstone.

adsorption performance in a short reaction time, which provides a new idea for solving the problem of the emergency treatment of water bodies polluted by heavy metal.

3.2.4. Effect of Pb(II) Ion Content on the Adsorption Effect. The experiments on the effect of different Pb(II) ion contents on the adsorption of Pb(II) were carried out using a mudstone addition of $1 \text{ g} \cdot \text{L}^{-1}$, a solution pH of 6, and a reaction time of 90 min. Figure 7 shows the adsorption capacity and removal rate of the mudstone for different Pb(II) contents. It can be seen from Figure 7 that the Pb(II) adsorption capacity of the mudstone increased continuously as the Pb(II) ion content increased, while the removal efficiency exhibited a decreasing trend. On the one hand, the active sites and exchangeable ions on the surface of a certain mass of mudstone material are limited, and when the ionic strength increases to a certain degree, the adsorption sites and functional groups on the surface of the mudstone are reduced. On the other hand, the active sites and exchangeable ions on the surface of a certain mass of mudstone material are limited, and when the ionic strength increases to a certain level, the adsorption sites and functional groups on the surface of mudstone are fully utilized, and the material reaches adsorption saturation, resulting in the excess Pb(II) not being adsorbed, thus reducing the Pb(II) removal rate [26-28]. In addition, the Pb(II) removal efficiency of the mudstone was greater than 80% when the Pb(II) ion content was less than $30 \text{ mg} \cdot \text{L}^{-1}$, and it gradually decreased when the Pb(II) ion content was between $30 \text{ mg} \cdot \text{L}^{-1}$ and $50 \text{ mg} \cdot \text{L}^{-1}$, but remained above 75%. Therefore, under the double consideration of the removal rate and adsorption capacity,

the mudstone was more effective in removing Pb(II) ions from the solution with a lower Pb(II) ion content, but it also had some value in treating the solution with a high Pb(II) ion content [29, 30].

3.3. Adsorption Isotherm and Adsorption Kinetic Model Analysis

3.3.1. Analysis of the Adsorption Isotherm Model. The adsorption isotherm is the equilibrium state of the adsorption reaction when the reaction proceeds sufficiently at a specific temperature. When the adsorption reaction reaches equilibrium, there is a certain relationship between the ion concentration of the solution and the adsorption capacity of the adsorbent, and this dependence curve is the adsorption isotherm. It is possible to understand the trend of the isotherm under each parameter and to determine the strength of the adsorption performance. The equilibrium time is the time when the adsorption reaction reaches equilibrium, and the adsorption capacity corresponding to this time is the amount of equilibrium adsorption. The experimental results for the Pb(II) adsorption by mudstone from a solution were fitted using the following two models [31].

(1) Langmuir adsorption isotherm model

The adsorption model proposed by Langmuir in 1916 based on the theory of molecular motion is a commonly used equation for adsorption isotherms and has been widely used in the field of adsorption [32]. It is based on the assumption that the adsorption process is a dynamic process and that the



FIGURE 6: Effect of adsorption reaction time on the adsorption effect.



FIGURE 7: Effect of the initial Pb(II) concentration of the solution on the Pb(II) adsorption of the mudstone.



FIGURE 8: Langmuir fitting model.

desorption rate is the same as the adsorption rate when the adsorption reaction reaches equilibrium [33, 34]. It is applicable to adsorbents with a uniform volume distribution and when the adsorption reaction occurs between single molecular layers. The expression of its adsorption model equation is as follows [35]:

$$\frac{c_e}{q_e} = \frac{c_e}{q_m} + \frac{1}{(b \times q_m)}.$$
(2)

Where *b* is the adsorption equilibrium constant; q_e is the adsorption amount at adsorption equilibrium (mg·g⁻¹); q_m is the theoretical saturation adsorption amount (mg·g⁻¹); and c_e is the equilibrium concentration of the liquid phase after adsorption equilibrium (mg·L⁻¹).

(2) Freundlich adsorption isotherm model

The Freundlich adsorption isotherm assumes that the adsorption process is a nonhomogeneous process, i.e., the adsorption sites on the surface of the adsorbent are irregular and are not independent of each other, but there may be a synergistic effect between the adsorption sites, and it belongs to an empirical equation that is applicable to multicomponent layer adsorption and surface adsorption under nonideal conditions [36]. The Freundlich adsorption isotherm can be used to express different systems of bilayers and reversible adsorption processes by fitting the following equation to the adsorption model [35]:

$$\lg q_e = \lg k + \frac{1}{n} \lg c_e, \tag{3}$$

Where k and n are the adsorption constants; q_e is the adsorption amount at adsorption equilibrium (mg·g⁻¹); and c_e is the equilibrium concentration of the liquid phase at adsorption reaction equilibrium (mg·L⁻¹).

Based on the results presented in Figures 8 and 9 and Table 2, both adsorption isotherm models can represent the adsorption process of the heavy metal Pb(II) by mudstone, but the correlation coefficient of the Langmuir isotherm model is higher(0.991), and it has a higher degree of linearity. This indicates that the Langmuir isotherm model is more suitable for the adsorption process of the heavy metal Pb(II) by mudstone. The correlation coefficient of the Freundlich adsorption isotherm model is 0.958 (i.e., >0.95), which indicates that the adsorption of the heavy metal Pb(II) by the mudstone occurred in a unimolecular layer structure, while the correlation coefficient of the Freundlich adsorption isotherm model is 0.958> (i.e., >0.95), which indicates that there is also a multimolecular layer reaction in the adsorption of the heavy metal Pb(II) by the mudstone [37]. The maximum adsorption capacity fitted using the Langmuir isotherm model was $54.975 \text{ mg} \cdot \text{g}^{-1}$. The empirical constant derived from the Freundlich adsorption isotherm model is n = 1.771, 1 < 1.771 < 10, indicating that the adsorption reaction easily proceeds and that the reaction is difficult when n < 0.5 [38]. In summary, it can be concluded that the adsorption of the heavy metal Pb(II) by the mudstone is a relatively complex process, and single-molecular-layer



FIGURE 9: Freundlich fitting model.

TABLE 2: Parameters	of	adsorption	isotherms.
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Models		Langmuir isotherm mod	Freundlich isotherm model			
Parameters	R^2	$Q_{\rm max}~({\rm mg}{\cdot}{\rm g}^{-1})$	$B (L \cdot mg^{-})$	R^2	$K (L \cdot g^{-})$	n
Mudstone	0.991	54.975	0.161	0.958	8.900	1.771



FIGURE 10: Pseudo-first-order kinetic fitting model.



FIGURE 11: Pseudo-second-order kinetic fitting model.

TABLE 3: Ad	sorption ki	inetics para	meters.
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Models	Pseudo-first-order kinetic			Pseudo-second-order kinetic			
Parameters	$K_1 \ (\min^{-1})$	$q_e \ (\mathrm{mg} \cdot \mathrm{g}^{-1})$	R^2	$\begin{array}{c} K_2 \ (\text{mg} \cdot (\text{g} \\ \text{min})^{-1}) \end{array}$	$q_e \ (\mathrm{mg} \cdot \mathrm{g}^-)$	R^2	
Mudstone	0.0868	26.875	0.96	0.0046	29.155	0.993	

adsorption and multimolecular-layer adsorption coexist and jointly affect the adsorption of the heavy metal Pb(II) by the mudstone.

3.3.2. Adsorption Kinetic Analysis. Adsorption kinetics is the study of the rate, time, and mechanism of adsorption and other characteristics of the reaction. The concentration of the adsorbent and the adsorbent mass can affect the rate of the adsorption reaction, and they are also closely related to the contact time. Usually, the analysis of adsorption kinetics is performed using the pseudo-primary kinetic model and the pseudo-secondary kinetic equation to fit the adsorption process of the studied ions and to predict the equilibrium adsorption capacity [39]. The expressions of the fitted equations are presented shown.

First-order equation [40]:

$$\ln\left(q_e - q_t\right) = \ln q_e - k_1 t. \tag{4}$$

Secondary equation [41]:

$$\frac{t}{q_t} = \frac{1}{\left(k_2 q_e^2\right)} + \frac{t}{q_e}.$$
 (5)

In (4) and (5), k_1 is the pseudo-first-order adsorption equilibrium rate constant (min⁻¹), k_2 is the pseudo-secondorder adsorption equilibrium rate constant (mg·(g min)⁻¹); q_e is the equilibrium adsorption of lead by the mudstone at adsorption equilibrium (mg·g⁻¹); and q_t is the adsorption of the heavy metal Pb(II) by the mudstone at time t (mg·g⁻¹).

Based on the results presented in Figures 10 and 11 and Table 3, we conclude that the adsorption reaction between the mudstone and the heavy metal Pb(II) has a relatively high degree of fitting for both the pseudo-first-order kinetic model and the pseudo-second-order kinetic model, but the R^2 value of the pseudo-second-order kinetic model is larger than that of the pseudo-first-order kinetic model, so the pseudo-second-order kinetic model is more consistent with the adsorption process of the heavy metal Pb(II) in a water body on mudstone. The theoretical adsorption capacity of $29.155 \text{ mg} \cdot \text{g}^{-1}$ obtained from the fitted results is comparable to the adsorption capacity of $26.658 \text{ mg} \cdot \text{g}^{-1}$ obtained from the experiments presented in the previous section, which further indicates that the pseudo-second-order kinetic model is more consistent with the adsorption of Pb(II) by the mudstone.

4. Conclusions

In this study, a mudstone composed of clay mineral material with abundant reserves in China was used as the research object, and the effects of the influencing factors, such as the amount of mudstone addition, solution pH, reaction time, and initial Pb(II) concentration of the solution, on the adsorption of Pb(II) from water bodies by a composite clay mineral material (mudstone) were investigated through static adsorption experiments. The main conclusions of this study are as follows.

The mechanism of using mudstone as a remediation material for lead-contaminated water was analyzed. The main clay minerals contained in the mudstone were $CaCO_{3}$, SiO₂, CaAl₂O₄·10H₂O, and CaFe₄O₇, among which the silicate minerals were dominant. Its surface structure was rough, and pores and fissures were developed. The clay minerals were abundant, and the cation exchange capacity, specific surface area, large pore size, and rich content of clay minerals indicate that using this mudstone to remediate lead-contaminated water using the adsorption mechanism is feasible. Regarding the factors affecting the adsorption of the Pb(II) in the solution by mudstone, the best Pb(II) adsorption effect of the mudstone in the static adsorption experiments was achieved when the amount of mudstone addition was $1 \text{ g} \cdot \text{L}^{-1}$ and the pH was 6. The best Pb(II) adsorption effect of the mudstone was achieved under these conditions, and the removal efficiency can reached 85.5%. Regarding the adsorption reaction time, the Pb(II) removal efficiency of the mudstone was close to 75% at 30 min, and the Pb(II) adsorption capacity and removal rate of the mudstone were close to the highest value at 60 min, with a removal efficiency of close to 88.8%. After 60 min, the adsorption capacity and removal rate did not change significantly as the reaction time increased, and they tended to become stable. The initial Pb(II) concentration of the solution also affected the adsorption of Pb(II) by the mudstone. The higher the initial concentration was, the higher the adsorption capacity was, and the lower the removal efficiency was. The data obtained from the adsorption experiments on the adsorption of the heavy metal Pb(II) by the mudstone were linearly fitted, and it was concluded that the Langmuir isotherm model was more suitable for describing the adsorption of the heavy metal Pb(II) by the mudstone. In addition, the fitting results indicate that the adsorption of the heavy metal Pb(II) by the mudstone occurred in a single molecular layer structure; while the correlation coefficient of the Freundlich isotherm model was 0.958 (i,e.,> 0.95). This also indicates that the adsorption process of the heavy metal Pb(II) by the mudstone also involved a reaction in multimolecular layers. The R^2 value of the pseudo-secondary kinetic model is larger than that of the pseudo-first-order kinetic model, so the pseudo-secondary kinetic model is more consistent with the adsorption of the heavy metal Pb(II) by the mudstone. This also indicates that the adsorption of the heavy metal Pb(II) by the mudstone was dominated by chemisorption.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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