

Research Article

Synthesis of Porous MgAl-LDH on Micelle Template and Its Application for Efficient Treatment of Oilfield Wastewater

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Abstract

In this paper, a series of porous hierarchical Mg/Al layered double hydroxides (named as LDH, TTAC-MgAl-LDH, CTAC-MgAl-LDH and OTAC-MgAl-LDH) were successfully synthesized by a simple green hydrothermal method using wormlike micelles formed by salicylic acid and surfactants with different carbon chain lengths (0, 14, 16 and 18) as soft templates. BET, XRD, FTIR, TG and SEM characterizations were carried out in order to investigate structure and properties of the prepared materials. The results showed that the porous hierarchical CTAC-MgAl-LDH had large specific surface area and multiple pore size distribution which could effectively increase the reaction area and allow better absorption capability. Benefiting from the unique architecture, CTAC-MgAl-LDH exhibited a large adsorption capacity for sulfonated lignite (231.7mg/g) at 25°C and pH of 7, which outperformed the traditional LDH (86.05mg/g), TTAC-MgAl-LDH (108.15mg/g) and OTAC-MgAl-LDH (110.51mg/g). The adsorption process of sulfonated lignite followed the pseudo-second-order kinetics model and conformed to Freundlich isotherm model with spontaneous heat absorption, which revealed that electrostatic adsorption and ion exchange were the main mechanisms of action for the adsorption. In addition, CTAC-MgAl-LDH showed a satisfactory long-time stability, and its adsorption capacities were still as high as 198.64 mg/g after two adsorption cycles.

INTRODUCTION

Sulfonated lignite (SL) is produced by introducing sulfonic acid group-SO₃H into condensed aromatic rings and aliphatic side chains of coal following sulfonation with concentrated sulfuric acid [1,2]. As its low viscosity and great dispersibility, SL is employed in petroleum exploration as a filtrate reduction, viscosity reducer, and pressure-reducing agent [3-5]. During the oil recovery process of deep shale, however, a large amount of highly concentrated and difficult-to-degrade drilling fluid wastewater containing sulfonated lignite macromolecules will be generated, causing deterioration of ecosystems as well as water quality and easily reacting with chlorine used in water treatment to produce carcinogens [6-10]. There are many methods to treat sulfonated lignite from drilling wastewater, such as gravity separation method, membrane separation method, flocculation method, salting-out method, activated sludge method and biological filter method [11-14]. However, most of them have shortcomings such as non-renewable raw materials, high operating costs and incomplete treatment of pollutants. Therefore, finding an effective method to treat SL in drilling fluid wastewater is crucial to the protection of water resources.

Layered double hydroxides (LDHs) are anionic clay minerals

with thermal stability, ion exchange properties, memory effects and acid-base dual properties [15-17]. Yao et al., used G-LDH prepared by hydrothermal method to achieve efficient removal of MO from wastewater by ion exchange [18]. Despite showing satisfactory results in the field of water treatment, traditional LDHs are prone to agglomeration after calcination under high temperature leading to their poor dispersion and consequently poor performance in removing pollutions in oilfield wastewater. To solve above problems, the preparation of LDHs with porous structures is highly desirable. Different chemical and physicochemical methods have been employed to prepare diversified porous adsorption materials. The template synthesis, which uses either hard templates or soft templates, is the most commonly used method [19]. However, hard template requires a multistep synthetic process and gives low-product yield [20]. Utilizing soft template is promising due to its simple and effective control of the morphology and size of the synthesised material by the choice of template agent [21]. Studies have shown that surfactants and organic counterions (such as salicylic acid) usually self-assemble into a series of wormlike micelles which built delicate large porous structure so as to give great potential to prepare ordered porous materials [22,23].

In this work, porous MgAl-LDH was prepared under a

hydrothermal condition by employing worm-like micelles derived from trimethyl ammonium chloride with different carbon chain lengths (tetradecyl trimethyl ammonium chloride, cetyl trimethyl ammonium chloride and octadecyl trimethyl ammonium chloride). High efficient adsorption performance was expected over this porous materials and adsorbent conditions, parameters that may affect the adsorption, including pH adsorbent dosage were evaluated. Both kinetic and equilibrium isotherm models were applied to establish the rate of adsorption and the adsorption capacity. Furthermore, the comparative characterizations of CTAC-MgAl-LDH before and after adsorption were well conducted to explore the corresponding adsorption mechanism towards SL.

MATERIALS AND METHODS

Materials

All chemicals including trimethyl tetradecyl ammonium chloride (TTAC), cetyl trimethyl ammonium chloride (CTAC), octadecyl trimethyl ammonium chloride (OTAC), salicylic acid (SA), $Mg(NO_3)_2 \cdot 6H_2O$, $Al(NO_3)_3 \cdot 9H_2O$, urea, sodium hydroxide (NaOH), hydrochloric acid (HCl) and absolute ethanol were analytical grade without any further purification and supplied from Xi'an Chemical Reagent Factory (Xi'an, Shaanxi, China). Sulfonated lignite was purchased from Tarim, Xinjiang, China. In addition, deionized water was used to formulate the solution.

Preparation of porous MgAl-LDH

Hierarchical porous MgAl-LDH was prepared by hydrothermal method using micelles as soft templates. Firstly, 0.69g of salicylic acid and 3.64g of CTAC were dispersed into 100 mL of distilled water and stirred at 60 °C for 60min to get a micelle solution. Then, $Mg(NO_3)_2 \cdot 6H_2O$, $Al(NO_3)_3 \cdot 9H_2O$ with molar ratio of 3:1:10 were dissolved in 100mL distilled water to get a metal salt solution. Subsequently, the metal salt solution was slowly added into the micelle under stirring to make them fully mixed. Next, the formed suspension was transferred to an autoclave, and then the sealed container was placed in the roller heating furnace at 160 °C for 6 h. Finally, the obtained precipitate was washed with deionized water and ethanol by centrifugation until the solution reached a pH of 7 and subsequently dried at 80 °C overnight. The obtained sample was labeled as CTAC-MgAl-LDH, and the porous hydrotalcites with surfactants TTAC and OTAC were prepared by the same method as TTAC-MgAl-LDH and OTAC-MgAl-LDH, respectively. For comparison, the traditional MgAl-LDH in the absence of surfactant solution was prepared and designated as LDH.

Characterization of Materials

The phase structures of samples were characterized by X-ray diffractometer (JDX-3530, Tokyo, Japan) with Cu K α radiation and a scanning speed of 2 ° min⁻¹ at a 40kV voltage and a 40mA current. All IR measurements were performed on a Nicolet 5700 FTIR spectrometer (Thermo Electron Co., Waltham, Massachusetts, America) at room temperature in the region of 4000-500 cm⁻¹.

Thermogravimetric (TG) analysis was investigated using a TGA/SDTA 851 thermal analyzer from 25°C to 800°C under an inert nitrogen atmosphere at a heating ratio of 10°C min⁻¹. Scanning electron microscopy (SEM) images were captured using a field-emission scanning electron microscope (JSM-6390A).

Adsorption Experiments

In this typical adsorption experiment process, 0.04g of adsorbent was added into 100 mL of a sulfonated lignite solution with an initial concentration of 100 mg/L. The mixtures were placed in a magnetic stirrer at room temperature, and the sulfonated lignite concentration was determined by UV-vis spectrophotometry at the wavelength maximum absorbance of 300nm. In the adsorption kinetics study, 0.04g of adsorbent was added to a 250 mL beaker containing 100 mL sulfonated lignite solutions with 100 and 200 mg/L concentration respectively. In the adsorption isotherm experiment, 0.08 g of adsorbent was added to 50mL of sulfonated lignite solutions with concentrations of 100, 200, 300, 400, and 500mg/L, respectively. Adsorption thermodynamic analysis was carried out by adding 0.08g of adsorbent to 50mL of a sulfonated lignite solution (200mg/L) at 298.15 and 303.15K. The adsorption capacity (q_t) at any given time and at equilibrium was calculated according to the following equation:

$$q_t = \frac{(c_0 - c_t) \times v}{m} \quad (1)$$

where C_0 (mg/L) and C_e (mg/L) are the initial and equilibrium concentrations(mg/L) of sulfonated lignite, respectively; V (L) is the volume of solution; and m (g) is the mass of the adsorbent.

RESULTS AND DISCUSSION

Structural Characterization of Porous MgAl-LDH

Figure 1 showed XRD patterns of the sample synthesized by 3:1 mole ratio of Mg/Al at 160°C for 6 h. The 2 θ peaks located at 11.6°, 23.5°, 34.9°, 39.5°, 47.0°, 60.9° and 62.1° are ascribed to the diffractions of basal planes of (003), (006), (012), (015), (110), (018) and (113) of LDH materials [24]. It can be indicated that the surfactants with different carbon chain lengths can all

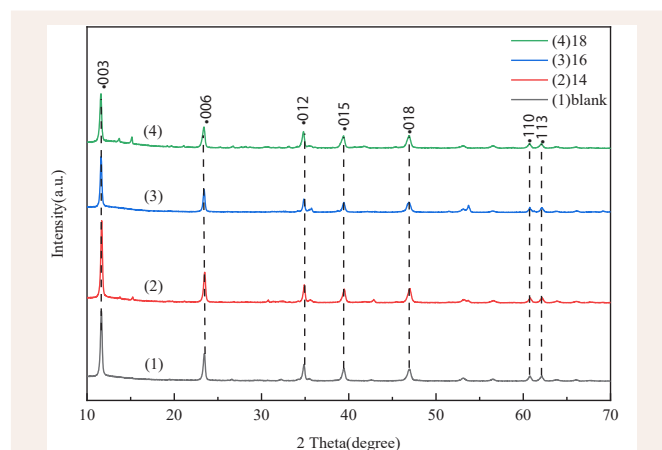


Figure 1 XRD patterns of LDH at different alkyl carbon chain lengths.

induce the orderly deposition of metal salt solutions, resulting in the preparation of LDH materials with good layered structures. In addition, CTAC-MgAl-LDH with a carbon chain length of 16 showed the lowest diffraction peak compared to other MgAl-LDHs, indicating that the micelle-templated hydroxalcite prepared with CTAC as surfactant had the best dispersion, which was favorable to enhance the adsorption activity of CTAC-MgAl-LDH to SL.

The surface properties (such as specific surface area and pore-size distribution) are important factors of adsorbent, and N_2 -adsorption/desorption measurements (Figure 2a), are performed over LDH and CTAC-MgAl-LDH. LDH and CTAC-MgAl-LDH displayed a type IV isothermal with H4 hysteresis loops and a type IV isothermal with H3 hysteresis loops, respectively, indicating the presence of mesopores. In addition, CTAC-MgAl-LDH had a large hysteresis loop and showed a significant adsorption slope at higher adsorption pressures ($p > 0.8$), which was attributed to the improved adsorption-desorption capacity of the material due to the macroporous structure. This is further verified by the pore size distribution curve (Figure 2b). As can be seen from the graph, CTAC-MgAl-LDH exhibited a wide size distribution (5-80 nm) and was mainly concentrated between 5 and 20 nm, indicating that the sample was hierarchical porous materials with mesopores and macroporous [25].

The BET surface area, pore volume, and pore diameter of the relative samples determined via N_2 -adsorption/desorption measurements are listed in Table 1. Compared with LDH, the introduction of micelle template significantly increases the specific surface area from 19.2143 to 174.2408 m^2/g . Increase of pore size was observed for CTAC-MgAl-LDH from 2.4240 to 4.7213 nm. In addition, the macropore volume of CTAC-MgAl-LDH was found to be increased to 0.1985 cm^3/g which indicates that the macropores structure after adding micelle template provided a high adsorption potential for SL.

FTIR spectra of samples were performed to analyze chemical structure. Figure 3 presented the FTIR spectra of LDH and CTAC-MgAl-LDH, respectively. The broad and strong absorption peak observed at 3452 cm^{-1} was assigned to the stretching vibration of the O-H groups in the hydroxide layer and the water molecules. The absorption bands at 1355 cm^{-1} was attributed to the asymmetric stretching vibration of C-O, indicating the existence of the carbonate anion in the MgAl-LDH [26]. And the absorption peaks at 500 cm^{-1} to 900 cm^{-1} are related to metal-oxygen and metal-hydroxyl vibrations in the hydroxalcite lattice. Compared with LDH spectra, CTAC-MgAl-LDH showed two small and narrow peaks at 2920 and 2851 cm^{-1} which were attributed to CH_3 asymmetric and CH_2 -symmetric stretching vibrations carried by the surfactant, indicating a good interaction between micelles and hydroxalcite [27].

Thermal analysis experiments were employed to characterize the thermal stability of the as-prepared LDH and CTAC-MgAl-LDH. It can be observed from the Figure 4 that two weight loss steps both exist in LDH and CTAC-MgAl-LDH. The first step from room temperature to approximately 240°C corresponded

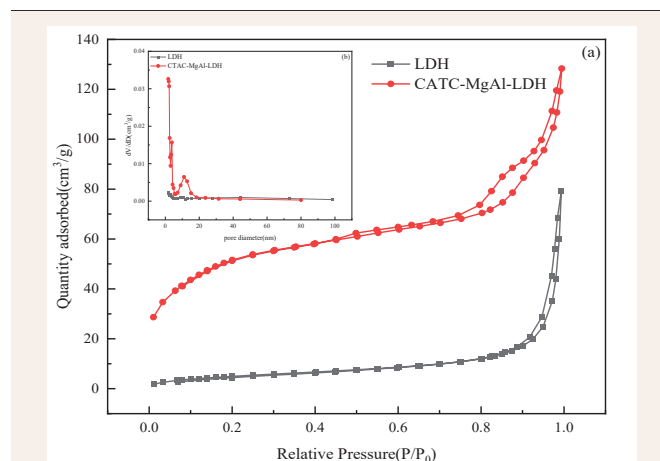


Figure 2 N_2 adsorption-desorption isotherms (a) and pore size distribution curve (b) of LDH.

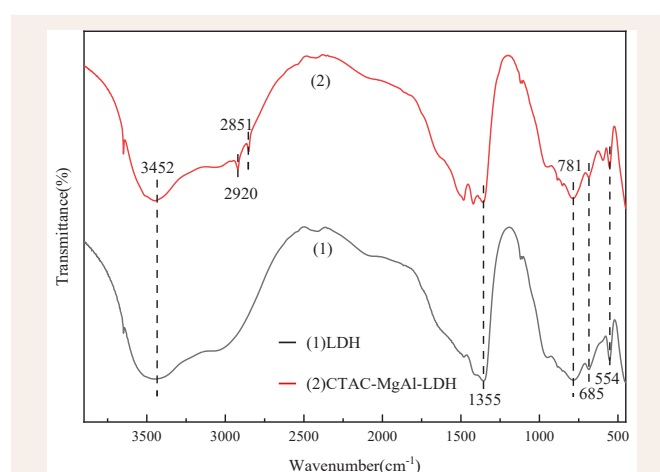


Figure 3 FTIR spectra of MgAl-LDH prepared by different method.

Table 1: BET surface area, pore volume and pore diameter of LDH

Sample	the specific area (m^2/g)	Pore volume (cm^3/g)	Pore diameter (nm)
LDH	19.2143	0.1225	2.4240
CTAC-MgAl-LDH	174.2408	0.1985	4.7213

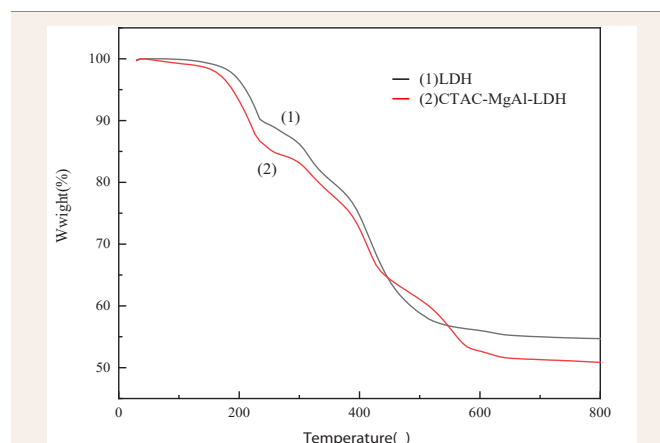


Figure 4 FTIR spectra and (b) TG curves of MgAl-LDH.

to the removal of physisorbed water, interlayer water and the dehydroxylation of the LDH layers. The second weight loss step in the temperature range from 240 to 600°C was due to the dehydroxylation of the hydrotalcite layers accompanied by the decomposition of interlayer carbonate anions [28]. The micellar template weakens the interaction of interlayer anions with the laminate, making it easier to achieve mutual exchange of anions. This is illustrated by the higher weight loss of the CTAC-MgAl-LDH carbonate anion (47.15%) compared to LDH (43.67%) at 600°C.

Adsorption Performance

Effect of different adsorbents: Sulfonated lignite was chosen as the target contaminant to study the adsorption behavior of as-prepared samples. Under the conditions of 25°C, an initial pH of 7, an adsorbent dosage of 0.4g/L, and a sulfonated lignite initial concentration of 100mg/L, the adsorption performance of adsorbent prepared by surfactants with different carbon chain lengths is shown in Figure 5. From the result, it can be seen that the prepared hydrotalcite derived from micellar template had a significantly better removal efficiency of sulfonated lignite with increasing the carbon chain length from 0 to 16. The best removal efficiency was found over 16 carbon chain length with the adsorption capacities of 231.7 mg/g. However, when the carbon chain length of surfactant with 18 was introduced, the adsorption capacity and removal rate decreased to 110.51 mg/g and 44%, respectively. It should be due to the increasing of viscosity of the surfactant with increasing carbon chain length causing the agglomeration of OTAC-MgAl-LDH and poor dispersion of samples suggested as the result of XRD [29].

Effect of adsorbent dosage: The adsorbent dosage is of great significance to the adsorption process of sulfonated lignite. In the research, the effect of adsorbent dosage was analyzed by performing the adsorption tests with varying amount (0.2 to 1.0g/L) of adsorbent at an initial SL concentration of 100 mg/L, a reaction temperature of 25°C, and an initial pH of 7 of the solution. It can be seen from Figure 6, as the amount of adsorbent

increased, the equilibrium adsorption capacity obviously decreased with removal efficiency and reached a maximum value of 88.4% when the adsorbent dosage is 0.4g/L. This trend was expected, because higher dosages of adsorbent might cause greater availability of surface area and exchangeable binding sites. However, it was found that the removal rate was basically unchanged, even after increasing the amount of adsorbent due to the saturation adsorption of CTAC-MgAl-LDH [30].

Effect of solution pH: The pH of the solution is acknowledged as one of the important factors that affect the adsorption performance of the adsorbent. It may considerably effect on the degree of ionization, surface charge and protonation of the functional groups of the adsorbent [31]. Therefore, the effect of solution pH on SL adsorption performance over CTAC-MgAl-LDH was evaluated with an initial pH ranging from 3 to 11 at an initial SL concentration of 100 mg/L, an adsorbent dosage of 0.4g/L, and a temperature 25°C. It is evident from the Figure 7 that the adsorption of SL by CTAC-MgAl-LDH occurs more easily under acidic conditions because of a large amount of H⁺ is attached to the surface of hydrotalcite under acidic conditions,

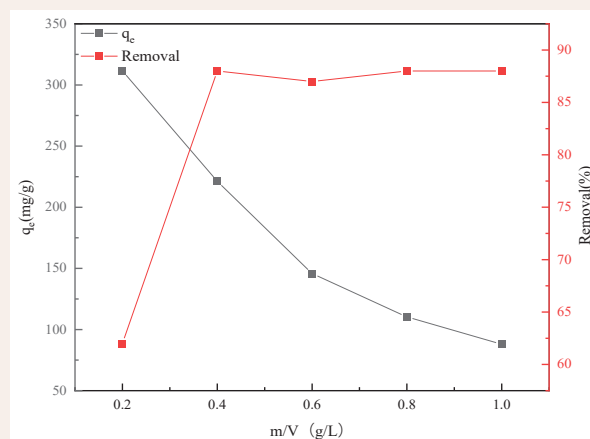


Figure 6 The effect of adsorbent dosage on SL adsorption for CTAC-MgAl-LDH.

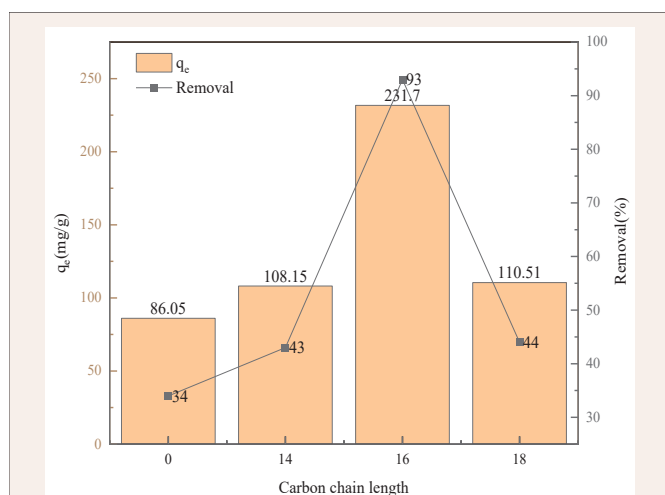


Figure 5 Effect of carbon chain length on sulfonated lignite adsorption.

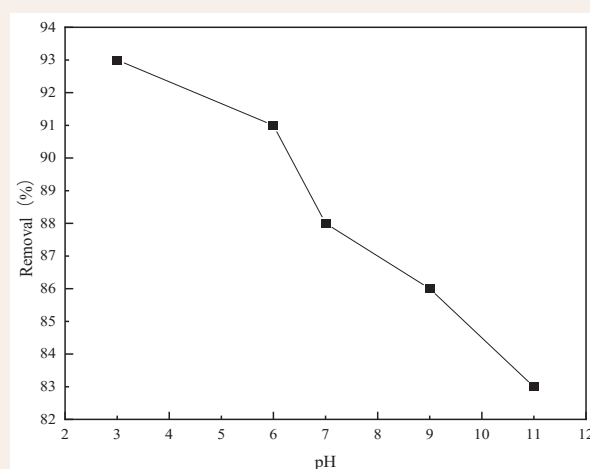


Figure 7 Effect of initial solution pH on SL adsorption using CTAC-MgAl-LDH.

and it is easy to generate electrostatic gravitational force with the negatively charged sulfonic acid ions to promote the adsorption. Furthermore, the decrease of removal cannot be avoided when the pH of solution increased up to 11 due to a large amount of negatively charged OH⁻ and sulfonic acid ions giving a competitive adsorption effect [32].

Adsorption kinetics study: The adsorption kinetics illustrates the pollutants adsorption rate and eventually explores the mechanism of adsorption and the rate limiting steps involved. The effects of contact time of CTAC-MgAl-LDH and SL on the adsorption property were investigated by performing experiments at different SL concentrations (100 and 200 mg/L) and varying contact times at 25°C and pH of 7. As shown in Figure 8, at low initial concentration (100 mg/L), the adsorption capacity can reach to 350 mg/L during the first 90 min due to the abundance of adsorption sites on the adsorbent surface. After a period of time, the remaining empty adsorption sites are difficult to be occupied due to the repulsive forces between the sulfonated lignite molecules and the bulk phase [33], resulting in a low adsorption rate until equilibrium is reached. Different adsorption time was required to reach equilibrium at different initial SL concentration. The equilibrium times of 120 and 350 min corresponded to the initial concentrations of 100 and 200 mg/L, which indicates that the higher SL concentration, the longer time was need to reach equilibrium [34].

To investigate the adsorption process of SL on CTAC-MgAl-LDH, the pseudo firstorder, pseudo second-order, intra particle diffusion and liquid film diffusion models were used to fit the experimental results. The fitting isotherm and kinetic parameters obtained by the linear regression are shown in Figure 9 and Table 2, respectively. From the results, it can be seen that the correlation coefficient (R^2) obtained from the pseudo-second-order kinetic model (R^2 was in the range of 0.996-0.998) was higher than that obtained from the pseudo-first-order kinetic model (R^2 was in the range of 0.906-0.917). Furthermore, the equilibrium adsorption values calculated by the second order model (q_e,cal) matched well with experimental adsorption

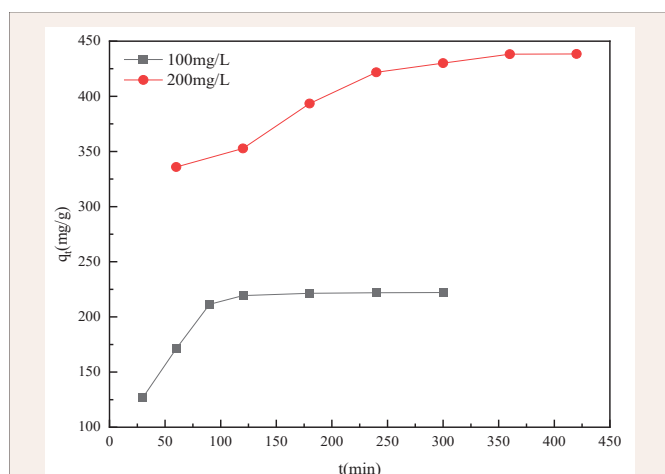


Figure 8 Effect of contact time on SL adsorption using CTAC-MgAl-LDH for initial SL concentrations of 100 and 200 mg/L.

Table 2: Parameters of the four dynamics models

Kinetic model	Parameter	Concentration (mg/L)	
		100	200
Pseudo-first-order	q_e (mg/g) model	98.87	618.19
	K_1 (h^{-1})	0.0213	0.0171
	R^2	0.906	0.917
Pseudo-second-order	q_e (mg/g) model	240.38	473.93
	q_e (mg/g) experimol/Lent	222.46	438.77
	K_2 (g/m gh)	0.00022	0.00007
	R^2	0.996	0.998
Intra particle diffusion	K_{11} (mg/gh ^{1/2})	21.024	9.917
	R_1^2	0.998	0.906
	K_{12} (mg/gh ^{1/2})	0.422	3.53
	R_2^2	0.860	0.917
Liquid film diffusion	K_{1d} (h^{-1})	0.0213	0.0171
	R^2	0.906	0.901

results (q_e,exp), which further confirmed that the kinetics of adsorption by CTAC-MgAl-LDH for the SL was best described by the pseudo second order model, which indicated that the rate controlling mechanism for adsorption was chemisorption caused by the electron exchange or sharing between the adsorbate and adsorbent [35]. In addition, it was found that the linear fitting correlation coefficient of the intra-particle diffusion model could reach up to 0.998, while the linear fitting correlation coefficient of the liquid diffusion model was between 0.901 and 0.906, thus indicating that the intra-particle diffusion model was the main rate control step of adsorption.

Adsorption isotherm: Adsorption isotherm studies usually describe the equilibrium adsorption behavior at constant temperatures [36]. In this work, the Langmuir, Freundlich and Dubinin-Redushkevich isothermal models fitted based on experimental data are shown in Figure 10, and the corresponding adsorption isothermal parameters are shown in Table 3. R^2 obtained by the Freundlich isotherm model is greater than 0.998, and that by the Langmuir adsorption isotherm model is between 0.879-0.952. These values indicate that the adsorption process of the adsorbent conforms to the Freundlich isotherm model. Therefore, the adsorption process was dominated by reversible adsorption with different affinity and belonged to multilayer adsorption [37]. The values of n (1.0777 and 1.1393 at 298.15 and 303.15 K) for best-fit Freundlich model were greater than 1 indicating that the adsorption process of sulfonated lignite proceeded easily. The values of activation energy calculated in the D-R model were 170.2 and 219.0J/mol at 298.15 K and 303.15K, which are both less than 8kJ/mol, indicating that electrostatic gravity is the main force in the adsorption process [38].

Thermodynamic study of adsorption: To confirm the nature of the adsorption process, experimental data for SL adsorption under equilibrium at different temperatures were used to evaluate the thermodynamic parameters. The fitting isotherms are shown in Figure 11, and the calculated parameters are summarized in Table 4. It can be found that the standard Gibbs free energy change value (ΔG) at different temperatures is negative, indicating that the adsorption process can be carried out spontaneously. The positive value of standard enthalpy

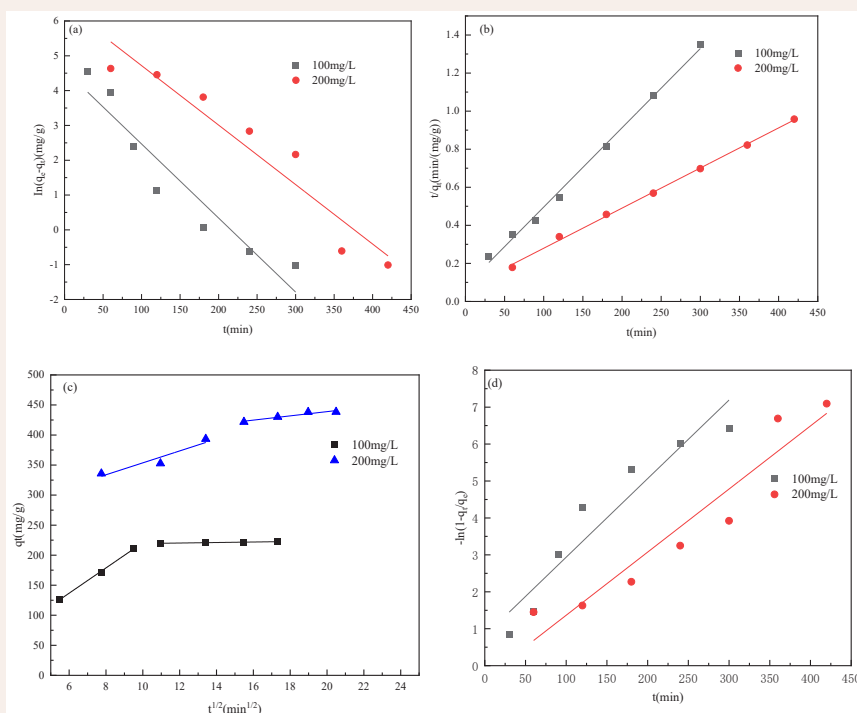


Figure 9 The four kinetic models for the adsorption of SL by CTAC-MgAl-LDH: (a) pseudo-first-order model, (b) pseudo-second-order model, (c) particle internal diffusion, and (d) liquid film diffusion.

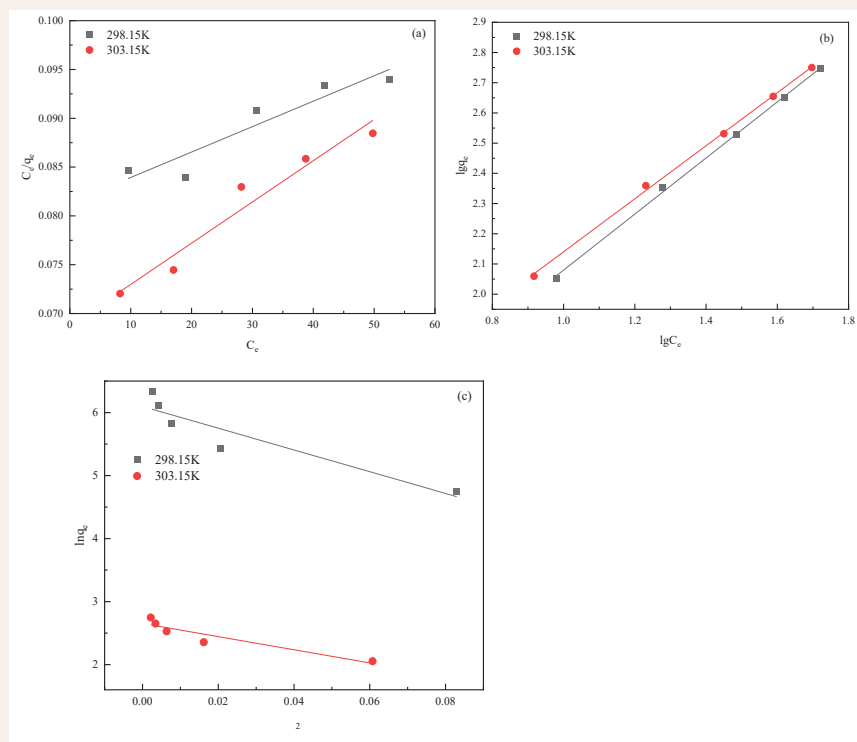


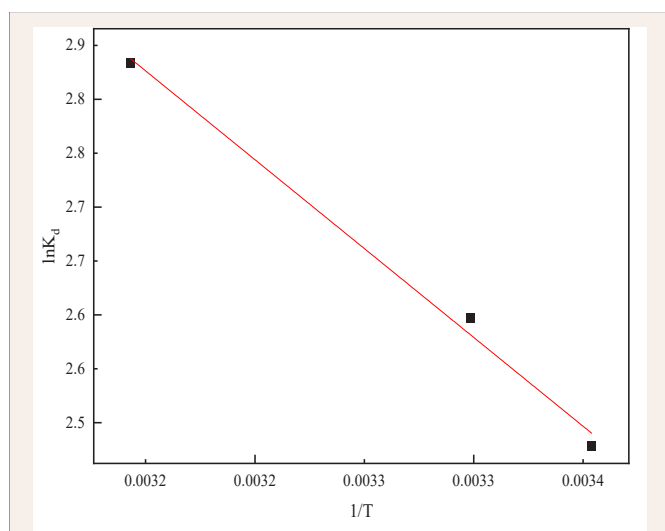
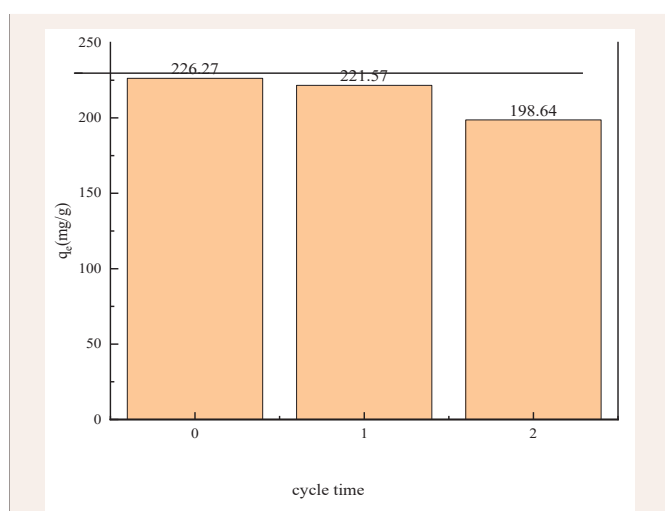
Figure 10 Adsorption isothermal models for adsorption of SL by CTAC-MgAl-LDH: (a) Langmuir model, (b) Freundlich model, and (c) Dubinin-Radushkevich (D-R) model.

Table 3: Isothermal model parameters of SL adsorption by CTAC-MgAl-LDH

Models	Parameters	T emperature	
		298.15 K	303.15 K
Langmuir	q_m (mg/g)	3839.51	2368.04
	b (mg/L)	47209.02	34439.21
	R^2	0.879	0.952
Freundlich	K_f (mg/g)	14.179	18.304
	n	1.078	1.139
	R^2	0.998	0.998
D-R	q_m (mg/g)	403.97	396.47
	β (mol ² /kJ ²)	17.255	10.421
	R^2	0.870	0.879
	E (J/mol)	170.2	219.0

Table 4: Thermodynamic parameters for the adsorption of SL by CTAC-MgAl-LDH.

T(K)	ΔS [J/(mol·k)]	ΔH [kJ/mol]	ΔG (kJ/mol)	R^2
298.15	66.68	13.71	-6.14	0.9935
303.15			-6.55	
318.15			-7.49	

**Figure 11** Adsorption thermodynamics of SL on CTAC-MgAl-LDH.**Figure 12** Regeneration performance of SL by CTAC-MgAl-LDH.

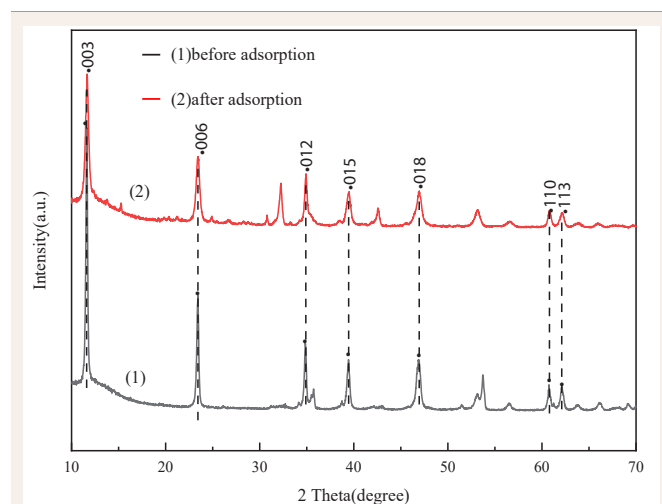
change (ΔH) can be demonstrated that the adsorption process is an endothermic process. Therefore, an appropriate temperature increase is beneficial for promoting the adsorption of SL by CTAC-MgAl-LDH, which was consistent with the experimental results of temperature effects. Simultaneously, the positive value of standard entropy change (ΔS) of adsorption reflects that the process of adsorption is an entropy-increasing process [39].

Regeneration of adsorbent

To be an economical and effective adsorbent in the oilfield wastewater treatment process, an adsorbent that could be easily regenerated and reused is crucially important and extremely welcome [40]. Adsorbent regeneration is the process of reproducing the adsorbent that has been used in the adsorption process. In the experiment, a NaOH solution was used to study the regeneration of the CTAC-MgAl-LDH. At room temperature, the CTAC-MgAl-LDH with saturated adsorption was immersed in an aqueous solution with a pH of 13 and stirred for 12h to achieve the desorption process, which was the adsorbent for primary regeneration after repeated washing. The regeneration performance of the CTAC-MgAl-LDH was investigated when the initial concentration of the sulfonated lignite was 200mg/L at the 25 °C and pH of 7. It can be seen from the result of Figure 12 that after two cycles of regeneration, the adsorption capacity of the hierarchical MgAl-LDH on SL slightly decreased from 226.27 to 198.64mg/g, reflecting the potential for practicality of prepared CTAC-MgAl-LDH. The decrease on adsorption affinity can be attributed to the loss of adsorbent during the adsorption cycle and the incomplete desorption of some adsorption sites of SL on CTAC-MgAl-LDH surface.

Characterisation of CTAC-MgAl-LDH before and after adsorption

Figure 13 showed the XRD plots of CTAC-MgAl-LDH before and after adsorption, from which it can be seen that the adsorbent still has the characteristic crystalline of MgAl-LDH

**Figure 13** The XRD patterns of CTAC-MgAl-LDH before and after adsorption.

after the adsorption of organic pollutants. Furthermore, since regeneration of the adsorbent required desorption under alkaline conditions, the diffraction peaks at 32.2° and 43.4° were assigned to the (200) and (220) crystal planes of NaCl generated by the combination of Na^+ in NaOH and Cl^- in CTAC. It can be inferred that the adsorption process is mainly the anion exchange between the hydroxyl layers. It can also be seen that the adsorption of organic matter between the hydroxyl layers during the adsorption process destroys its ordered lamellar structure to a certain extent, which leads to a decrease in the intensity of the hydroxyl characteristic diffraction peaks.

CTAC-MgAl-LDH after adsorption of SL was characterized by FTIR (Figure 14), measurements. It can be seen that the similarity of frequency bands before and after adsorption indicated that the functional groups such as CH_3 asymmetric, CH_2 -symmetric stretching vibration, metal-oxygen and metal-hydroxy vibration of the adsorbed material were well maintained. Compared with CTAC-MgAl-LDH, after interaction with water containing SL, the sample showed an asymmetric stretching vibration of $\text{O}=\text{S}=\text{O}$ at 1118 cm^{-1} and a $\text{C}=\text{C}$ stretching vibration from benzene ring skeleton in aromatic at 1577 cm^{-1} , indicating that the SL was adsorbed on the surface of CTAC-MgAl-LDH. In addition, the stretching vibration band of $\text{O}-\text{H}$ shifts from 3446 cm^{-1} to 3452 cm^{-1} , which associated with the coordination bond is formed by hydroxyl, carboxyl groups in sulfonated lignite and hydroxyl groups in CTAC-MgAl-LDH [41]. Since regeneration of the adsorbent required desorption under alkaline conditions, the diffraction peaks at 32.2° and 43.4° were assigned to the (200) and (220) crystal planes of NaCl generated by the combination of Na^+ in NaOH and Cl^- in CTAC.

Figure 15 shows scanning electron micrographs of porous hydroxylate (CTAC-MgAl-LDH) prepared under hydrothermal conditions before and after adsorption. As can be seen from Figure 15a, the CTAC-MgAl-LDH before adsorption not only has the hexagonal lamellar structure of conventional hydroxylate, but also three-dimensional flower-like structure formed in the presence of surfactants. The hexagonal morphology of LDH still remained after adsorption (Figure 15b), even agglomeration occurred to some extent which indicates that the layered structure is destroyed.

Adsorption mechanism of hierarchical MgAl-LDH

Based on experimental and characterization results, both physisorption and chemisorption existed in the SL adsorption of CTAC-MgAl-LDH. The initial stage of adsorption is dominated by physical adsorption, while chemisorption plays a dominant role in the middle and late stages of adsorption. The sulfonated lignite molecules decompose into sulfonate ions ($\text{R}-\text{SO}_3^-$) after dissolved in the solution as shown in Figure 16. Then, $\text{R}-\text{SO}_3^-$ were attracted by cations (Mg^{2+} , Al^{3+}) in the interlayered CTAC-MgAl-LDH due to the electrostatic force. Subsequently, ion exchange occurs between $\text{R}-\text{SO}_3^-$ adsorbed on the surface of CTAC-MgAl-LDH and CO_3^{2-} in LDH layers, which effectively reduced the remaining concentration of sulfonated lignite in the water column. This is consistent with the results of.

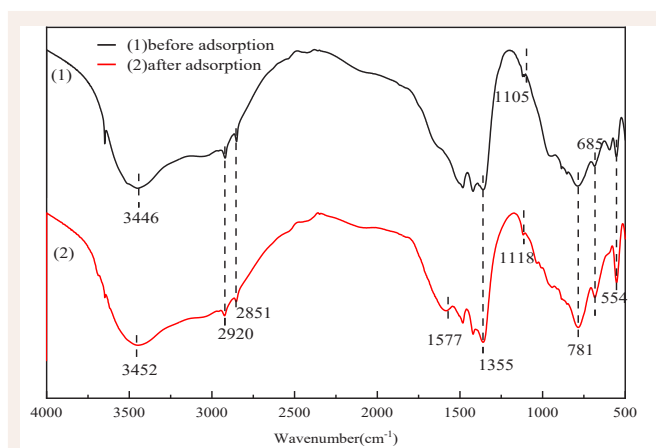


Figure 14 The FTIR spectra of CTAC-MgAl-LDH before and after adsorption.

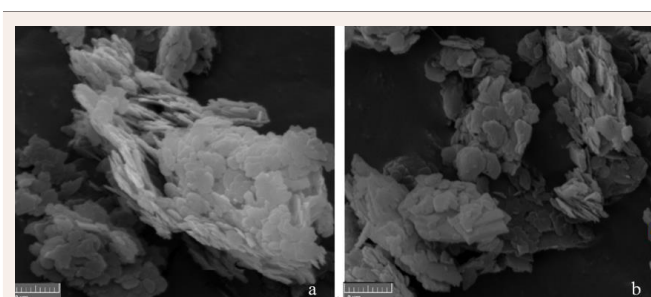


Figure 15 SEM image of template hydroxylate before and after adsorption.

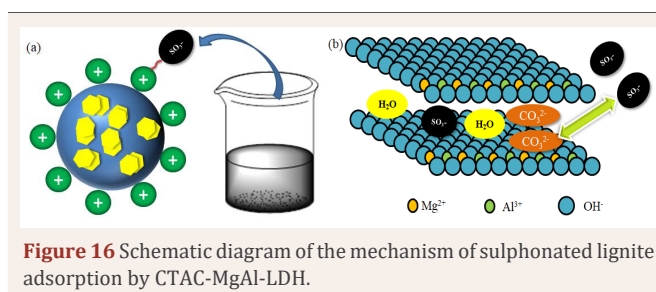


Figure 16 Schematic diagram of the mechanism of sulfonated lignite adsorption by CTAC-MgAl-LDH.

CONCLUSIONS

In summary, LDH, TTAC-MgAl-LDH, CTAC-MgAl-LDH and OTAC-MgAl-LDH were synthesized through a hydrothermal method using micelles as templates. The samples showed the best removal efficiency of SL at a carbon chain length of 16 (CTAC-MgAl-LDH) with the adsorption capacities of 231.7 mg/g . The lower removal rate for samples with carbon chain length less than 16 (LDH, TTAC-MgAl-LDH) was due to the inability of the micellar template and the salt solution to form an optimal three-dimensional network structure. For carbon chain lengths greater than 16 (OTAC-MgAl-LDH), excessive micelle viscosity makes the prepared samples poorly dispersed, which in turn affects its adsorption performance. The as-obtained CTAC-MgAl-LDH gives a very high surface area, porous hierarchical structure and excellent dispersity, resulting in promoting the

efficient exchange of interlayer anions of CTAC-MgAl-LDH with $R-SO_3^-$ of SL. Research on adsorption kinetics and isotherms indicated that the adsorption process followed pseudo-second-order kinetics and Fredrich isotherm models, respectively, and therefore belongs to multi-layer chemisorption. Consequently, CTAC-MgAl-LDH exhibits superior adsorbability and excellent reusability in the adsorption of SL macromolecules. It is expected that the porous hierarchical CTAC-MgAl-LDH synthesized in this work is promising in the treatment of oilfield pollutants.

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