Synthesis of octyl-modified ordered mesoporous silica as a new nano sorbent for the removal of 2-chlorophenol from aqueous media

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ABSTRACT

Adsorption of 2-chlorophenol onto octyl-modified ordered mesoporous silica material from an aqueous solution was investigated systematically using batch experiments in this study. Hexagonal mesoporous silica (HMS) owning double pore paths and OD-HMS were synthesized by using cheap sodium silicate and a non-ion surfactant C16PyCl under room temperature here and characterized by X-ray diffraction (XRD), N₂ adsorption–desorption measurement, and Fourier Transform-Infrared (FT-IR). Results indicate that 2-chlorophenol adsorption is initially rapid and the adsorption process reaches a steady state after 5 min. The adsorption isotherms are well described by the Langmuir and the Freundlich models, the former being found to provide a better fit with the experimental data. The effects of temperature, pH, ionic strength, and humic acid on the adsorption are also examined. According to the experimental results, the amount of 2-chlorophenol adsorbed decreases with increases of temperature from 288 to 308 K, and pH from 2.0 to 11.0, the amount of 2-chlorophenol adsorbed increases with an increase of ionic strength from 0.001 to 0.1 mol/L. However, the amount of 2-chlorophenol adsorbed onto octyl-modified ordered mesoporous silica material shows notable difference in the presence of humic acid. The desorption process shows a reversibility of 2-chlorophenol adsorption onto octyl-modified ordered mesoporous silica material. Thermodynamic parameters such as Gibbs free energy are calculated from the experimental data at different temperatures. Based on the results, it was found that octyl-modified ordered mesoporous silica shows significant adsorption for 2-chlorophenol. This might be due to hydrophobic interaction among the octyl functional groups and 2-chlorophenol.

Key words | adsorption, 2-chlorophenol, desorption, isotherm, OD-HMS

INTRODUCTION

Chlorophenols are a widespread class of water pollutants that are known to cause serious human health problems; hence these chemicals are found in the list of priority pollutants of the Environmental Protection Agency (EPA) (1984) and the European Union (EU) (2001). They are widely used in industry as intermediates in the production of dyes, plastics and pharmaceuticals. Chlorophenols are commonly found in the wastewater of the pulp and paper industry, which pollutes groundwater resources (Patton et al. 1992). In addition, the chlorination process of tap water leads to the generation of chlorophenols from phenols, which are responsible for the unfavorable smell.

Several methods such as oxidation with hydrogen peroxide (Mokrini et al. 1997), wet oxidation (Poulopoulos et al. 2007), biological degradation (Kennedy et al. 1992), membrane filtration (Lin et al. 2002; Das et al. 2008), emulsion liquid membrane processes (Park et al. 2006), ion exchange (Chan & Fu 1998), electrochemical oxidation (Polcaro & Palmas 1997), reverse osmosis (Goncharuk et al. 2002), photocatalytical degradation (Alberici & Jardin 1994),
adsorption (Backhaus et al. 2001; Jain & Jayaram 2007) and biosorption (Antizar-Ladislao & Gall 2004) have been used for the removal of phenols. The most common disadvantage of such methods is the fact that at trace level the efficiency decreases markedly. Adsorption is usually considered the best choice due to its versatility. However, the use of relatively expensive adsorbents such as activated carbons may pose a serious problem from an economic standpoint. Thus, an alternative adsorbent for 2-chlorophenol removal is required.

Adsorption of organic compounds onto siliceous materials has been investigated intensively by many researchers (Shu et al. 1997; Anderson 2000; Chang et al. 2005, 2004). Siliceous materials such as zeolite, silica, and clay are found widespread in the environment and they are environment friendly materials for environmental contaminant remediation. In order to enhance the adsorption capacity, modifications of siliceous materials by cationic surfactants have been made in previous studies (Li & Bowman 1998; Lemic et al. 2006). The modified materials exhibit excellent adsorption properties for organic pollutants like perchloroethylene, atrazine, lindane, and diazinone. Additionally, the synthesis of ordered mesoporous silica with high surface area has attracted much attention in several areas because of its possible industrial application as reaction catalyst, catalyst support, chemical sensor, adsorbent for environmentally hazardous chemicals, and electrical and optical devices (Zhao et al. 1996; Selvam et al. 2001). Hexagonal mesoporous silica (HMS), one member of the mesoporous molecular sieve family, possesses a high specific surface. Such material is characterized by large surface areas, narrow pore size distribution, and moderate hydrophobic character. Cooper and Burch reported that M41S possessed large adsorption capacities for efficient elimination of both cyanuric acid and p-chlorophenol from aqueous solution and the adsorption capacity can be regenerated by ozonation (Cooper & Burch 1999). Additionally, Wang et al. (2006) pointed out that MCM-22 could be an effective adsorbent for the removal of methylene blue, crystal violet, and rhodamine B from aqueous solution. Nevertheless, there are scarce reports on the use of octyl-modified HMS for 2-chlorophenol removal from water and more effort is required in this area in order for such an adsorbent to be practically applied.

Therefore, the purpose of the present research was to investigate the adsorption characteristics of 2-chlorophenol from aqueous solutions onto octyl-modified HMS material. As a first step in the adsorption of 2-chlorophenol, it is necessary to quantify the equilibrium time during adsorption. In turn, adsorption isotherms are conducted in batch experiments under different temperatures and then thermodynamic parameters are calculated. Influencing parameters such as pH, ionic strength, and humic acid are evaluated to characterize the extent of 2-chlorophenol adsorption. Finally, desorption of 2-chlorophenol from octyl-modified HMS has been studied to determine its reversibility of adsorption.

**METHODS**

**Materials**

2-Chlorophenol (99%; without further purification) and humic acid were purchased from Shanghai Chemical Factory. Cetylpyridine chloride (98.5%) was obtained from Yingyuan of Shanghai Chemical Factory. Sodium silicate was purchased from Tianjin Baishi Chemical. All solvents used here were of analytical HPLC grade. The initial solution pH was adjusted by introducing appropriate amounts of acid (HCl) or base (NaOH) solutions. For all experimental work, Milli-Q ultrapure water was used. The ionic strength (I) was adjusted by NaCl solution. Unless otherwise stated, all reagents used in this study were analytical grade.

**Preparation of HMS mesoporous silica**

The HMS was synthesized in an acidic medium using conventional literature recipes (Patiparn & Takizawa 1997). Typical procedures using C16PyCl and sodium silicate powder are shown below. The C16PyCl surfactant (5.37 g) was added into 250 mL of water. This solution was vigorously stirred with optional heating. After further stirring for a prescribed time (usually
3 h) at room temperature, the precipitate was filtered, washed thoroughly with water, dried in an oven at 313 K, and finally calcined in air for 5 h at 823 K. The BET surface area of the calcined HMS was 864 m²/g and the pH_{zpc} (pH of zero charge point) was 5.0.

**Preparation of octyl-modified HMS (OD-HMS)**

Silanization of HMS with n-octyltrimethyloxysilane, denoted as OD-HMS, was carried out as follows: after drying 5 g of HMS at 423 K under vacuum for 24 h, the sample was put into a 250 mL, three-neck round flask under N₂ flow. 140 mL of dichloromethane and a magnetic stirrer were added to the flask and stirred. 1.8 g of 1-methyl-2-pyrrolidinone and 3.6 g of n-octyltrimethyloxysilane were added under N₂ flow. The mixture reacted under reflux at 333 K for 4 h. After that, the mixture was filtered and washed twice with 50 mL of chloroform and 50 mL of ethanol. The sample was then dried at 313 K in vacuum for 4 h. Hydrophobicity of HMS was increased by grafted ligands.

**Characterization of OD-HMS**

A powder X-ray diffraction (XRD) pattern was recorded on a Rigaku Rotaqflex diffractometer equipped with a rotating anode and CuKa radiation.

The porosity characteristics of the mesoporous silica sorbent was determined by N₂ adsorption–desorption experiments performed at −196 °C on an Automatic Volumetric Sorption Analyzer using static sorption procedures. The sample was outgassed at 150 °C and 1.0 × 10⁻³ mbar for a minimum of 12 h prior to analysis. BET surface areas were calculated from the linear part of the BET plot. Pore size distribution was estimated from the adsorption branch of the isotherm by the BJH method.

Fourier Transform-Infrared (FT-IR) spectra (10 scans per measurement) were recorded with 4 cm⁻¹ resolution using a FT-IR spectrometer in the wavenumber range of 4,000–400 cm⁻¹, applying the KBr-pellet technique (~0.10 wt% mesoporous material in KBr matrix). FT-IR spectra of the mesoporous sorbent were obtained after equilibration at atmospheric temperature and humidity. The spectra presented were baseline corrected after subtracting the spectra of a pure KBr pellet from the spectra of the sorbent OD-HMS.

**Adsorption experiments**

The effect of contact time on 2-chlorophenol adsorption onto OD-HMS was studied based on 2-chlorophenol concentrations of 0.6 and 8 mg/L. The adsorption experiments were carried out by mixing 4.0 g OD-HMS samples with a 1,000 mL aqueous solution in a 2,000-mL stirred flask at a temperature of 298 K. Samples were taken out and centrifuged at 3,000 rpm at different times. Then the residual concentration of 2-chlorophenol was determined.

The adsorption isotherm experiments of 2-chlorophenol onto OD-HMS were performed on the basis of a batch experiment. A given amount of adsorbent (0.2 g) was placed in a 100-mL conical flask, into which 50 mL of a 2-chlorophenol solution with varying concentrations was added. The experiments were performed in a temperature-controlled water bath shaker for 1 h at a speed of 170 rpm. After the adsorption reached equilibrium, the solutions were centrifuged and analyzed for the remaining concentration of 2-chlorophenol. Then flowing experiments were undertaken under common conditions. The amount of 2-chlorophenol adsorbed onto OD-HMS was calculated from the mass balance equation as

\[ q_e = \frac{(C_0 - C_e)V}{M} \]  

where \( q_e \) (mg/g) is the amount of 2-chlorophenol adsorbed per gram of OD-HMS at equilibrium; \( C_0 \) (mg/L) and \( C_e \) (mg/L) are the initial and equilibrium liquid-phase concentration of 2-chlorophenol, respectively; \( V \) (L) is the volume of 2-chlorophenol solution, and \( M \) (g) is the mass of OD-HMS used. To check reproducibility, 2-chlorophenol adsorption was carried out in duplicate. The relative deviations met with the requirement of less than 5%.

**Desorption experiment**

Desorption isotherms were obtained from the adsorption samples in equilibrium. A solution containing OD-HMS was transferred into centrifuge tubes that were centrifuged at 3,000 rpm for 10 min with the centrifuge temperature...
being set at the incubation temperature. Then, 25 mL of the supernatant was removed and compensated for sampling by adding 25 mL of pure water. The tubes were placed on a reciprocating shaker for 1 h at 298 K. Preliminary kinetic studies showed that desorption could reach equilibrium state within 5 min. After shaking, the suspensions were centrifuged and 25 mL of the supernatant was collected for analysis.

**Analytical method**

The concentration of 2-chlorophenol was determined by gas chromatograph with flame ionization detector (FID), using a HP-5 capillary column (30 m × 320 μm × 0.25 μm). The injection volume was 2.0 μL, the temperature of inlet and FID was 280 °C, carry gas was pure N2, flow rate was 4.0 mL/min. Under these conditions, the retention time for 2-chlorophenol was 3.2 min.

**RESULTS AND DISCUSSION**

**Characterization of OD-HMS**

The powder low-angle XRD pattern of HMS and OD-HMS depicted in Figure 1 shows the occurrence of clear reflection peaks at 2.28° and 2.32° respectively. The unique diffraction peak pattern of this type of material indicated the absence of higher order. It corresponds to a wormlike structure. The sample exhibits single d_{100} reflection, confirming short-range hexagonal symmetry of the material, and an ordered mesoporous HMS formed (Ke & Liu 2007). This kind of weak XRD adsorption peak may be led by a lower ordered pore path structure. In the process of forming mesoporous material, the lower level of hydrogen bonding between non-ion surfactants and the surface of inorganic matter made the inorganic matter species form a different mesoporous structure in different districts. In this way, it led to a poor pore path order with hexagonal accumulation. In addition, some researchers think that this kind of material with an exiguous grain generates a lower diffraction peak in the XRD spectrum (Corma 1997), but these exiguous grain and relevant short pore path structures are beneficial for transmission of material in the process of adsorption and catalysis.

Figure 1 shows that the hexagonal structure of the mesoporous material was still apparent after the function, but the reflection peak (100) descended and broadened. This indicates that the crystal order structure of the pore became degraded because of the organic-matter-filled pore path, which limits the manifold crystal lattice and decreases the reflection peak.

The physical adsorption–desorption of nitrogen is an effective technique for determining the textural properties of mesoporous materials. The N2 adsorption–desorption isotherms for the parent HMS and OD-HMS mesoporous silica are shown in Figure 2. In isotherms of HMS and OD-HMS, a hysteresis loop of obvious adsorption and desorption can be observed which indicates the presence of a mesoporous framework. The HMS and OD-HMS exhibit typical IV type adsorption isotherms. The surface areas for the parent HMS and OD-HMS silica samples are 845 and 639 m²/g, the mean pore diameters are 3.4 and 3.6 nm and the mean pore volumes are 0.77 and 0.49 cm³/g, respectively.

From the BJH pore size distribution plot of HMS (Figure 3), the pore diameter distribution range can be seen to be 2.1–3.2 nm and 3.2–4.4 nm, a material of double pore path. OD-HMS forms a single pore path material after octyl-modified with a pore diameter distribution range of 3.1–4.4 nm. This is because the grafted...
long-chain molecules entered part of the small pore after octyl-modification, taking up part of the available space. As a result, a part of the larger pore was only determined in the course of the mensuration adsorption-desorption of nitrogen, causing OD-HMS to have a single pore path.

Figure 4 shows the FTIR spectrum of the synthesized HMS and OD-HMS. In the spectrum of HMS, the adsorption band at 469 cm$^{-1}$ is caused by the bending vibration of Si–O. The band at 796 cm$^{-1}$, which corresponds to the Si–O and Si–O–Si vibrations, is due to the greater ionic character of the Si–O group. The band due to asymmetric Si–O–Si stretching vibration is at 1,085 cm$^{-1}$. These three absorption bands are the typical characteristic vibration bands of completely formless SiO$_2$. This proves that synthetic HMS is a mesoporous material with a characteristic band structure. The broad band at 3,463 cm$^{-1}$ is attributed to the O–H bond stretching vibration of adsorbed water molecules. The corresponding bending vibration mode can be also clearly identified at 1,631 cm$^{-1}$. As reported elsewhere (Shylesh & Singh 2005), absorption vibration at 960 cm$^{-1}$ is generated by the large amount of Si–OH on the surface of a pure silica mesoporous molecular sieve.

In the spectrum of OD-HMS, asymmetric and symmetric CH$_2$ stretching vibrations are generated at 2,920 and 2,854 cm$^{-1}$ by reaction between the silicane reagent and –Si–OH on the surface of HMS. Further more, absorption peak intensity lowers at 3,463, 1,631 and 960 cm$^{-1}$, indicating that –OH on the surface of HMS are replaced by octyl.

Effect of chemical modification

In order to evaluate the efficiency of the prepared adsorbents, the equilibrium adsorption of the chlorophenols was studied as a function of equilibrium concentration. The adsorption isotherms of 2-CP on OD-HMS and HMS are shown in Figure 5. It is seen that the order of adsorption
in terms of the amount adsorbed (mg/g) at different conditions is: OD-HMS > HMS. OD-HMS registers higher adsorption capacity (0.66 mg/g) than the untreated mesoporous HMS (0.31 mg/g). The higher adsorption capacity of OD-HMS may be because of the hydrophobicity created by the octyl group.

Effect of contact time on 2-chlorophenol adsorption

As shown in Figure 6, apparent adsorption equilibrium is generally obtained within 5 min for the initial 2-chlorophenol concentration of 0.2 mg/L. Thereafter, no detectable concentration changes occurred (<60 min) after adsorption equilibrium (5 min). It is assumed here that the adsorption takes place primarily at easily accessible surface sites, requiring no diffusion into micropores.

Adsorption isotherms

Adsorption equilibrium data, expressed by the mass of adsorbate adsorbed per unit weight of adsorbent and liquid phase equilibrium concentration of adsorbate, are usually represented by adsorption isotherms, which is of importance in the design of adsorption systems. The adsorption isotherms of 2-chlorophenol onto OD-HMS at temperatures of 288, 298, and 308 K are shown in Figure 7. All adsorption isotherms are nonlinear with curvatures concave to the abscissa. The adsorption of 2-chlorophenol onto OD-HMS decreases from 0.75 to 0.59 mg/g when temperature is increased from 288 to 308 K at an initial concentration of 8 mg/L. The decrease in the equilibrium adsorption of 2-chlorophenol with temperature demonstrates that 2-chlorophenol removal by adsorption onto OD-HMS favors a low temperature. In order to describe the adsorption isotherm, two important isotherms are selected in this study, the Langmuir and Freundlich isotherms:

\[ q_e = \frac{Q_0 K_L C_e}{1 + K_L C_e} \]  

(2)

\[ q_e = K_F C_e^{1/n} \]  

(3)
where $q_e$ (mg/g) is the amount of 2-chlorophenol adsorbed per gram of OD-HMS at equilibrium; $C_e$ (mg/L) the equilibrium concentration of 2-chlorophenol in solution; $Q_0$ (mg/g) the maximum monolayer adsorption capacity; $K_L$ (L/mg) the constant related to the free energy of adsorption; $K_F$ [(mg/g)(L/mg)$^{1/n}$], a Freundlich isotherm constant for the system and the slope $1/n$, ranging between 0 and 1, indicative of the degree of nonlinearity between solution concentration and adsorption. The isotherm parameters and linear regression obtained from the fitting curves by Langmuir and Freundlich models are given in Table 1. It is clear that adsorption isotherms at different temperatures can be fitted well using two isotherm models. However, the Langmuir model is better able than the Freundlich model to describe the adsorption isotherm, as reflected by the correlation coefficients. This suggests that the adsorption is homogeneous, and the adsorption film is monomolecular. Subsequent equations can then use Langmuir constants to calculate the thermodynamic parameters. The maximum monolayer adsorption capacity, $Q_0$, defines the total capacity of OD-HMS for 2-chlorophenol adsorption and decreases with increasing temperature. A change in the maximum monolayer adsorption capacity with temperature is possibly due to the low hydrothermal stability of OD-HMS in water. At high temperatures, the structure of OD-HMS could collapse by mechanical compression through the hydrolysis of siloxane bonds in the presence of adsorbed water, which may decrease the amount of active sites. Moreover, when the interaction is exothermic, the adsorbate has a tendency to escape from the solid phase to the solution. Thus, a rise in temperature and excess energy supply will promote desorption.

The free energy ($\Delta G^0$) of 2-chlorophenol adsorption onto OD-HMS at different temperatures is calculated based on the adsorption isotherm by Singh et al. (2003):

$$\Delta G^0 = -RT \ln K_L$$

(4)

where $R$ (J/mol K) is the universal gas law constant; $T$ (K) the absolute temperature of solution, and $K_L$ (L/mol) the Langmuir constant. The values of $\Delta G^0$ are calculated from $-15.5$ to $-21.4$ kJ/mol. It is noted that the $\Delta G^0$ values are all negative, which indicate the feasibility and spontaneous adsorption of 2-chlorophenol onto OD-HMS.

Effect of pH on 2-chlorophenol adsorption

The pH of solution is one of the most important parameters affecting the adsorption process. In order to determine the effect of pH on adsorption capacity of OD-HMS, solutions were prepared at different pH ranging from 2.0 to 11.0. The dependence of pH on the adsorption of 2-chlorophenol onto OD-HMS is illustrated in Figure 8. Obviously, the

![Figure 8](https://iwaponline.com/ws/article-pdf/12/3/259/416795/259.pdf)

**Table 1** Parameters of adsorption isotherms of 2-CP onto OD-HMS at different temperatures

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Langmuir model</th>
<th>Freundlich model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Q_0$ (mg/g)</td>
<td>$K_L$ (L/mg)</td>
</tr>
<tr>
<td>288</td>
<td>11.65</td>
<td>0.020</td>
</tr>
<tr>
<td>298</td>
<td>43.86</td>
<td>0.0042</td>
</tr>
<tr>
<td>308</td>
<td>4.040</td>
<td>0.031</td>
</tr>
</tbody>
</table>
amount of adsorbed 2-chlorophenol \( (q_e) \) is decreased by increasing the pH value. At pH = 2.0, the uptake of 2-chlorophenol is 0.079 mg/g, while at pH = 10.0, the uptake of 2-chlorophenol is only 0.049 mg/g. It is apparent that solutions of pH = 2.0 gives the highest \( q_e \) value.

For adsorption onto a solid surface, six adsorption mechanisms are believed to exist (i.e., electrostatic interaction, ion exchange, ion-dipole interactions, coordination by surface metal cations, hydrogen bonding, and hydrophobic interaction \( (Lu \ et \ al. \ 1996) \)). Since 2-chlorophenol is a weak electrolyte compound \( (pK_a = 8.55) \), electrostatic interaction and ion-exchange mechanisms are negligible. The ion-dipole interactions between the charged surface and the weak electrolyte 2-chlorophenol are also expected to be negligible in this experiment. OD-HMS is hydrophobic. Therefore, the adsorption mechanisms could be contributed to by hydrophobic interaction. The possible explanation for the sharp decrease in 2-chlorophenol adsorption with the increase of pH could be that OD-HMS material is relatively stable with high acid resistance, whereas it degrades readily in basic solution that will destroy the structure of OD-HMS.

**Effect of ionic strength on 2-chlorophenol adsorption**

Since NaCl is often used as a stimulator in adsorption processes, the effect of ionic strength (adjusted by NaCl) on 2-chlorophenol adsorption has been determined and the results are presented in Figure 9. It indicates that the amount of adsorbed 2-chlorophenol onto OD-HMS increases with the increase of NaCl concentration of the solution. As 2-chlorophenol is a nonpolar hydrophobic chemical, increasing ionic strength will lead to a decrease of the solubility of 2-chlorophenol in water. Therefore, for 2-chlorophenol, increasing ionic strength should usually be accompanied by an increase in partition into OD-HMS.

**Effect of humic acid on 2-chlorophenol adsorption**

Humic acid exists extensively in surface water and it interferes with the adsorption of trace organic compounds on porous adsorbents such as powder activated carbon (PAC) by pore blockage and direct competition for adsorption sites \( (Newcombe \ et \ al. \ 2002) \). The effect of humic acid on 2-chlorophenol adsorption onto OD-HMS is shown in Figure 10. A given amount of humic acid was dissolved by 0.1 mol/L sodium hydroxide solution, then solution pH was adjusted to 7 by a hydrochloric acid solution, and final humic acid concentration was determined to be 400 mg/L. The 2-chlorophenol solution including 5 and 20 mg/L humic acid were confected by takeoff of 0.625 and 2.5 mL humic acid into 50 mL 2-chlorophenol solution respectively. The results suggest that the existence of humic acid at a concentration of 5 and 20 mg/L affects the extent of 2-chlorophenol adsorption. The amount of adsorbed 2-chlorophenol at humic acid concentrations of 0, 5 and 20 mg/L is about 0.79, 0.77 and 0.65 mg/g, respectively, at...
an initial concentration of 8 mg/L. This observation can be explained by the direct competition for adsorption sites. The reason is the limited number of adsorption sites available for the uptake of 2-chlorophenol at a fixed adsorbent dosage.

**Effect of different water substrates on 2-chlorophenol adsorption**

Different water substrates of 2-chlorophenol adsorbed onto OD-HMS are shown in Figure 11. The results suggest that different water substrates affect the extent of 2-chlorophenol adsorption. The amount of adsorbed 2-chlorophenol onto OD-HMS at an initial concentration of 8 mg/L is about 0.79, 0.46 and 0.38 mg/g in de-ionized water, tap water and songhuajiang water, respectively. This suggests that some compound in water affects the extent of 2-chlorophenol adsorption onto OD-HMS.

**Desorption of 2-chlorophenol by OD-HMS**

Desorption is one of the key processes affecting the ultimate fate of contaminants in solids. In order to evaluate the reversibility of 2-chlorophenol adsorption onto OD-HMS, desorption characteristics were also determined. Desorption isotherms of 2-chlorophenol adsorbed onto OD-HMS are shown in Figure 12. There is no hysteresis in Milli-Q water between adsorption and desorption. This suggests that the adsorption and desorption are reversible and the exchange of 2-chlorophenol between bulk water and OD-HMS can be realized with a similar mechanism. Thus, desorption could be predicted on the basis of adsorption isotherms.

**CONCLUSIONS**

Silanization of HMS with n-octyltrimethyldichlorosilane was demonstrated to adsorb 2-chlorophenol from aqueous solution. The results show that synthesized HMS has a double pore path and a great number of hydroxyls. It is a typical hexagonal mesoporous material. Mesoporous materials transition to one pore path from two pore paths after function. Chlorophenol can be adsorbed onto OD-HMS much more easily than onto HMS. The data obtained from adsorption isotherms at different temperatures fitted to the Langmuir model very well. The adsorption capacity for 2-chlorophenol decreased with an increase of temperature. It was found that increasing pH decreased the adsorption capacities. The result was attributed to destroying the structure of OD-HMS in basic solutions. Increasing ionic strength increased the extent of 2-chlorophenol adsorption. Increasing ionic strength leads to a decrease of the solubility of 2-chlorophenol in water. Therefore, for 2-chlorophenol, increasing ionic strength should usually be accompanied by an increase in partition into OD-HMS. The presence of humic acid had influence on 2-chlorophenol adsorption. The reason is the limited number of adsorption sites available for the uptake of 2-chlorophenol at a fixed adsorbent dosage. Desorption

![Figure 11](https://iwaponline.com/ws/article-pdf/12/3/259/416795/259.pdf)  
*Figure 11 | Effect of different water substrate on the adsorption of 2-CP onto OD-HMS (adsorption conditions: adsorbent dosage = 4 g/L, pH = 6, and temperature = 298 K).*

![Figure 12](https://iwaponline.com/ws/article-pdf/12/3/259/416795/259.pdf)  
*Figure 12 | Adsorption-desorption isotherms of 2-CP (adsorption conditions: adsorbent dosage = 4 g/L, pH = 6, and temperature = 298 K).*
isotherms showed that adsorption and desorption of 2-chlorophenol were reversible. Combined with pH effects, it was concluded that hydrophobic interaction was the main force to adsorb 2-chlorophenol from aqueous solution.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by the National Natural Science Foundation of China (NSFC, Project 50638020) and the National High Technology Research and Development Program of China (2007AA06Z339).

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First received 8 September 2009; accepted in revised form 8 September 2010