



Adsorption of naphthalene-derived compounds from water by chemically oxidized nanoporous carbon

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ARTICLE INFO

Article history:

Received 7 July 2008

Received in revised form 9 September 2008

Accepted 17 September 2008

Keywords:

PAHs

Chemically oxidized mesoporous carbon

Adsorption

Langmuir isotherm

ABSTRACT

In the present work, a chemically oxidized mesoporous carbon (COMC) with excellent adsorption properties towards naphthalene-derived compound was prepared by an acid surface modification method from mesoporous carbon (MC) through wet impregnation method. The structural order and textural properties of the prepared materials were studied by XRD, SEM, and nitrogen adsorption. The presence of carboxylic functional groups on the carbon surface was confirmed by means of FTIR analyses. Adsorption of naphthalene, 1-naphthol and 1,5-diaminonaphthalene on various mesoporous adsorbents such as COMC, MC were studied from solutions of different pH. The adsorption isotherms of polycyclic aromatics hydrocarbons were in agreement with a Langmuir model, moreover, the uptake capacity of naphthalene followed the order: COMC > MC.

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1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) are chemical species with two to six fused benzene rings which are well-known toxic hazardous pollutants of highly potent carcinogens that can cause tumors in some organisms [1]. In recent years, PAHs contamination in water systems has drawn increasing attention. PAHs originate from natural and anthropogenic sources. Anthropogenic sources include engine exhaust, industrial processes, crude oil, urban runoff, domestic heating systems, incinerators and smoke. Natural sources include terrestrial coal deposits, volcanic eruptions and forest fires. The main sources of PAHs in surface water are atmospheric deposition, runoff from contaminated soils and deposition from sewage discharges [2]. Most PAHs are hydrophobic with high boiling and melting points and electrochemical stability. Therefore, they can exist and be accumulated in soils or water for a long time [3].

Adsorption treatment provides a simple and universal approach to effectively removing organic pollutants from the aquatic environment. The removal of toxic pollutants from water is a problem, particularly when they are present in low concentrations. Several studies have focused on the fate and transport of these pollutants and the application of remedial technologies to manage them [4–10]. Activated carbons present an outstanding adsorption

capacity that stems from their high surface area, pore structure and surface chemical properties. These materials are effective adsorbents for priority pollutants, therefore being suitable for the decontamination of water and wastewater. These porous carbons are generally microporous and the preparation of carbon materials with well-ordered mesoporous structure would offer many application possibilities not only in the adsorption and separation of large molecules whose molecular sizes are too large to enter micropores but also in electrical double layer capacitors, gas separation, catalysis, water and air purification and energy storage. Recently, Ryoo et al. prepared ordered mesoporous carbons (CMK-x) from mesoporous silica templates such as MCM-48, SBA-1 and SBA-15 using sucrose as the carbon source [11–14]. Adsorption plays an important role in these processes. Therefore, the interactions of such compounds with the mesoporous carbon surface must be studied in detail. The mesoporous carbon materials adsorption capacity depends on quite different factors. Obviously, it depends on the mesoporous carbon's characteristics: texture (surface area, pore size distributions), surface chemistry (surface functional groups) [15–17]. It also depends on adsorptive characteristics: molecular weight, polarity, pK_a , molecular size, and functional groups. The influence of the texture and surface chemistry of nanoporous carbons in the adsorption of organic compounds has been studied for years, and many references on this topic can be found in the literature. The adsorption of organic molecules from aqueous solutions on nanoporous carbons has been recently reviewed [18,19], and it was shown that the specific mechanism by which the adsorption of many organic compounds takes place on this adsorbent is still ambiguous. Since the pioneer works

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of Coughlin and Ezra [20] and Mattson et al. [21] to other published more recently [22–25], it was found that the adsorption capacity is significantly affected by the carbonous adsorbent surface chemistry.

Different studies have been done on interaction between acid oxygen-containing surface groups and the adsorption of organic compounds in aqueous solution. There are two types of interactions between the adsorbate and the carbonous adsorbent: electrostatic and dispersive [17–19]. The former appears when the adsorbate is dissociated under the experimental conditions used; for the latter three mechanisms are proposed: π – π dispersion interaction mechanism, the hydrogen bonding formation mechanism, and the electron donor–acceptor complex mechanism. The π – π dispersion interaction mechanism is the most widely accepted [17,18]. The surface chemistry and solution pH are the most important factors controlling the adsorption process [26]. Most of the aromatic pollutants are found in water solution in the molecular state for a broad range of pH values. In this case, dispersive interactions are predominant, mainly because of the attraction between the π orbitals on the carbon basal planes and the electronic density in the adsorbate aromatic rings (π – π interactions). However, when the solution pH is very high or very low, ions may be present, so electrostatic interaction between them and charged functional groups on the carbon surface could be significant [17].

In this work, the influence of the texture and surface chemistry of mesoporous carbon adsorbent as well as the solution pH were systematically studied in the adsorption of different organic compounds. For this purpose, mesoporous carbon was modified by selected oxidative treatments, producing samples differing in the surface chemistry and textural parameters, to study their influence in the adsorption process. The pH effect was evaluated doing tests at different pH solution conditions. Interestingly, it has been found that the adsorption capability of chemically oxidized mesoporous carbon for PAHs molecules is much higher compared to that of pristine mesoporous carbon. Furthermore, Langmuir and Freundlich adsorption isotherms were studied to explain the sorption mechanism.

2. Experimental

2.1. Materials

The reactants used in this study were tetraethyl orthosilicate (TEOS) as a silica source, cetyltrimethylammonium bromide (CTAB) as a surfactant, sodium hydroxide (NaOH), sodium fluoride (NaF), deionized water for synthesis of mesoporous silica (MCM-48), sucrose as a carbon source, sulfuric acid as a catalyst for synthesis of mesoporous carbon, nitric acid as an oxidizer agent, naphthalene, 1-naphthol, and 1,5-diaminonaphthalene. All chemicals were of analytical grade from Merck.

2.2. Synthesis of silica template and MC

MCM-48 was prepared using CTAB as a surfactant and TEOS as a silica source, according to Shao et al. [27]. Briefly, 10 mL of TEOS was mixed with 50 mL of deionized water, and the mixture was vigorously stirred for 40 min at 35 °C, then 0.9 g of NaOH was added into mixture, and at the same time, 0.19 g of NaF was added into the mixture. After the NaF was added completely, the required content of sources, respectively, were added. After another 60 min of vigorously stirring, 10.61 g of CTAB was added to the mixture, and stirring continued for 60 min. The mixture was heated for 24 h at 393 K in an autoclave under static conditions, and the resulting product was filtered, washed with distilled water, and

dried at 373 K. The sample was calcined at 823 K for 4 h in air to remove the surfactant completely. The product thus obtained was referred to as MCM-48. Then 1.25 g sucrose and 0.14 g H₂SO₄ in 5.0 g H₂O was dissolved, and this solution were added to 1 g MCM-48. The sucrose solution corresponded approximately to the maximum amount of sucrose and sulfuric acid that could be contained in the pores of 1 g MCM-48. The resultant mixture was dried in an oven at 373 K, and subsequently, the oven temperature was increased to 433 K. After 6 h at 433 K, the MCM-48 silica containing the partially carbonizing organic masses was added with an aqueous solution consisting of 0.75 g sucrose, 0.08 g H₂SO₄ and 5.0 g H₂O. The resultant mixture was dried again at 373 K, and subsequently the oven temperature was increased to 433 K. The color of the sample turned very dark brown or nearly black. This powder sample was heated to 1173 K under vacuum using a fused quartz reactor equipped with a fritted disk. The carbon-silica composite thus obtained was washed with 1 M NaOH solution of 50% ethanol–50% H₂O twice at 363 K, in order to dissolve the silica template completely. The carbon samples obtained after the silica removal were filtered, washed with ethanol and dried at 393 K.

2.3. Chemical oxidation of MC

To introduce oxygen-containing functional groups on the carbon surface, MC was oxidized by nitric acid under optimal oxidation condition, such as nitric acid concentration, oxidation temperature [28]. 0.1 g of dried MC powder was treated with 15 mL of HNO₃ solution (2 M solution) for 1 h in the 80 °C under refluxing. After oxidation, samples were recovered and washed thoroughly with distilled water until the pH was close to 7.

2.4. Characterization

The X-ray powder diffraction patterns were recorded on a Philips 1830 diffractometer using Cu K α radiation. The diffractograms were recorded in the 2θ range of 0.8–10 with a 2θ step size of 0.01° and a step time of 1 s. Adsorption-desorption isotherms of the synthesized samples were measured at 77 K on micromeritics model ASAP 2010 sorptometer to determine an average pore diameter. Pore-size distributions were calculated by the Barrett–Joyner–Halenda (BJH) method, while surface area of the sample was measured by Brunauer–Emmett–Teller (BET) method. SEM images were obtained with JEOL 6300F SEM. The Fourier transform infrared spectra for the unmodified and modified samples were measured on a DIGILAB FTS 7000 instrument under attenuated total reflection (ATR) mode using a diamond module.

2.5. Adsorption studies

A stock solution of 30 mg L⁻¹ for each PAHs was prepared by dissolving an appropriate amount of the PAHs in ultra-pure water (18 M Ω cm) derived from a Milli-Q plus 185 water purifier. Batch adsorption isotherms were performed by shaking 500 mL amber Winchester bottles containing the required concentration of the PAHs in a Gallenkamp incubator shaker. The shaker was set at a temperature of 25 ± 1 °C and a speed of 150 rpm. Initial solution concentration of 0.02–0.14 mmol L⁻¹ was prepared by pipetting out the required amounts of the PAHs from the stock solution. The volume of solution in each bottle was maintained at 500 mL and the solutions were adjusted to pH 5. About 0.01 mg of each adsorbent was weighed accurately on aluminum foils using a Sartorius (Model BP 201D) analytical balance. The adsorbents were transferred carefully into the bottles using 50 mL solutions from the bottles. The bottles were shaken vigorously before shaking for dif-

ferent time in the incubator shaker (New Brunswick Scientific C25 Model).

The amount of PAHs adsorbed was calculated by subtracting the amount found in the supernatant liquid after adsorption from the amount of PAHs present before addition of the adsorbent by UV–vis spectrophotometer (UV mini 1240 Shimadzu). Absorbance was measured at wavelength (λ_{\max}) 275.5, 320 and 331 nm for determination of naphthalene, 1,5-naphthalenediamine and 1-naphthol, respectively [29,30]. Calibration experiments were done separately before each set of measurements with different concentrations of PAHs solutions. Centrifugation prior to the analysis was used to avoid potential interference from suspended scattering particles in the UV–vis analysis.

The adsorption capacities were calculated based on the differences of the concentrations of solutes before and after the experiment according to the following equation [31]:

$$q_e = \frac{(C_0 - C_e)V}{W} \quad (1)$$

where q_e is the concentration of the adsorbed solute (mmol/g), C_0 and C_e are the initial and final (equilibrium) concentrations of the solute in solution (mmol/L), V (mL) is the volume of the solution, and W (g) is the mass of the adsorbent.

2.6. Adsorption kinetics of PAHs

For the measurement of the time resolved uptake of PAHs onto adsorbents, 15 mL of distilled water was mixed with 60 mg of MC in a 500-mL flask for about 10 min. 285 mL of PAHs solution was quickly introduced into the flask (keeping the initial concentrations of the resulting solutions at 30 ppm) and stirred continuously at 20 °C. Samplings were done by fast filtration at different time intervals. The concentration of residual PAHs in the solution was determined and the adsorption amount q_t was calculated according to the following equation [32]:

$$q_t = \frac{(C_0 - C_t)V}{W} \quad (2)$$

where q_t is the adsorption amount at time t , C_0 is the initial concentration of PAHs solution, C_t is the concentration of PAHs solution at time t , and V is the volume of PAHs solution and m is the mass of MC.

3. Results and discussion

3.1. Characterization of the COMC and MC samples

The quality of the mesoporous carbon samples prepared in this study was examined by nitrogen adsorption–desorption analysis, X-ray diffraction (XRD) techniques and SEM image.

Nitrogen physisorption is the method of choice to gain knowledge about mesoporous materials. This method gives information on the specific surface area and the pore diameter. Calculating pore diameters of mesoporous materials using the BJH method is common. Former studies show that the application of the BJH theory gives appropriate qualitative results which allow a direct comparison of relative changes between different mesoporous materials.

The nitrogen sorption isotherms of the MC and COMC, have the typical type IV shape. Each isotherm shows a distinct hysteresis loop, which is characteristic of mesoporous adsorbents. This phenomenon is associated with capillary condensation in mesopores. Pores within porous materials are classified as micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm), in accordance with the classification adopted by the IUPAC. All of the pore size distribution curves suggest that mesopores are predominant, owing to

Table 1
Textural parameters of the MC and COMC employed in this study.

Adsorbent	d spacing (nm)	A_{BET} ($\text{m}^2 \text{g}^{-1}$)	V_p ($\text{cm}^3 \text{g}^{-1}$)
MC	3.4	1010.5	0.69
COMC	3.1	985.4	0.63

the presence in the pore size distribution curves of large peaks at pore diameters greater than 2 nm. Interestingly, the pore size distributions are essentially the same as before acid oxidation. The adsorption uptakes at relative pressure close to $p/p_0 = 0$ are identical. However, the total uptakes are slightly different, decreasing with the surface modification with acid. As shown in Table 1, the decreases in the specific surface areas and pore volumes are 2.5 and 9.5%, respectively. From the nitrogen sorption isotherms (Fig. 1) of mesoporous carbon type carbons before and after acid oxidation, it can be seen that after oxidation the obtained carbons still have type IV isotherms, indicating that mesoporosity is still preserved. However, the oxidation leads to a decrease in the total uptake of the oxidized carbons, which reflects the decrease of the total pore volume resulting from acid oxidation. Interestingly, the oxidized carbons essentially keep the bimodal pore size distribution, which is characteristic of the parent MC. The textural parameters listed in Table 1 clearly confirm the structural changes of oxidized MC. Especially, the variations of the surface area and pore volume are significant with the increase in the acid concentration.

In order to check the structural degradation, XRD data of COMC and MC were obtained on Philips 1830 diffractometer using $\text{Cu K}\alpha$ radiation of wavelength 0.154 nm. Fig. 2 shows the XRD peaks of the samples. The XRD patterns of COMC showed three diffraction peaks that can be indexed to (1 1 0), (2 1 0), and (2 2 0) in the 2θ range from 0.8° to 10° , representing well-ordered cubic pores [11]. The XRD patterns of MC carbon and COMC (in Fig. 2) show well-resolved reflections indicating that MC carbon nicely maintains its original structure even after the oxidation with 2 M nitric acid. For COMC sample, the cubic structure of MC was maintained well; but, the XRD reflections become less pronounced that might be due to the partial damage of the mesoporous (cubic) structure or due to the decreased contrast between walls and pores because of the cleavage of the carbon species from the pore walls.

The Scanning electron microscopy showed that the porous carbon particles did not retain the spherical morphologies for the silica template as in Fig. 3b. Also, the template synthesis did not follow a simple replication process for the structure of the mesoporous silica. Both the SEM images of the mesoporous carbon before and after surface oxidation showed rod-like morphology (Fig. 3a and b).

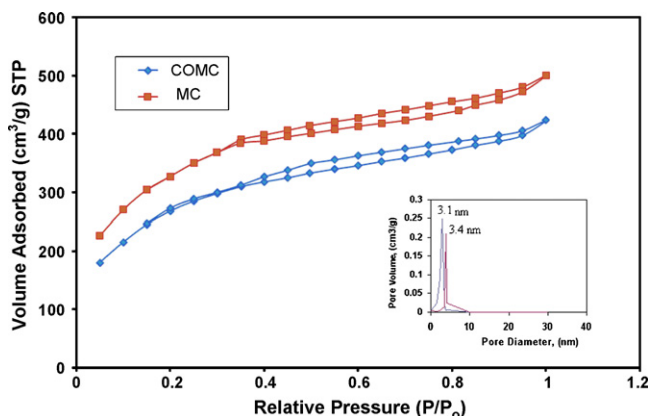


Fig. 1. Adsorption–desorption isotherms of nitrogen at 77 K on MC and COMC. The insert shows the BJH pore size distribution calculated from the desorption branch of the isotherm.

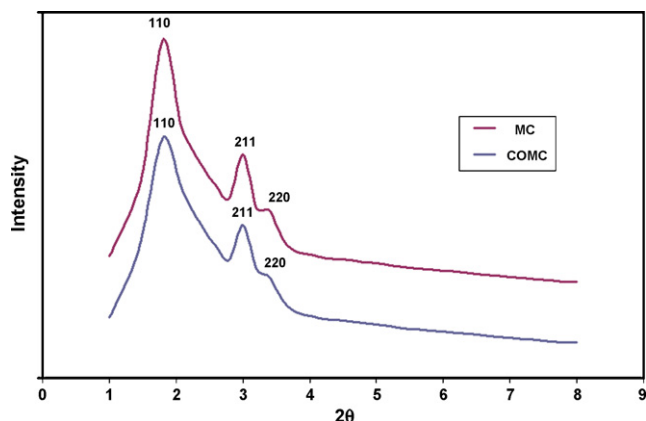


Fig. 2. XRD pattern of COMC and MC.

The length of these carbon rods was a little shorter after acid treatment, which was assumed to be caused by oxidation of the carbon surface.

The FT-IR technique was used to monitor changes on the surface of the ordered mesoporous carbon and the content of the introduced oxygen-containing functional surface group.

Fig. 4 shows the FT-IR spectra of MC and as treated COMC samples. A broad band at around 3450 cm^{-1} was observed in all

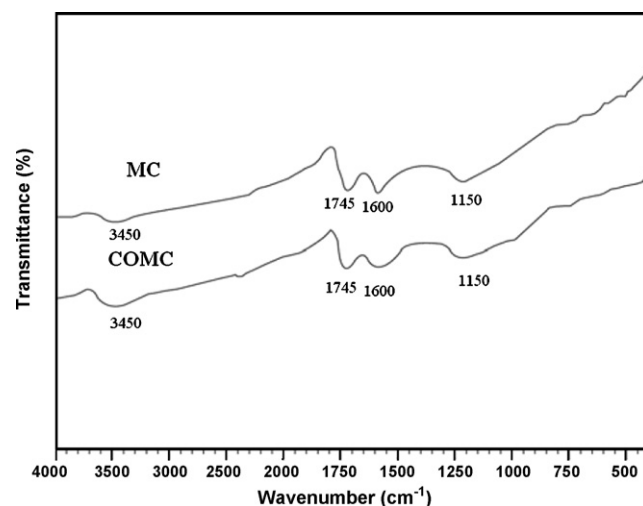
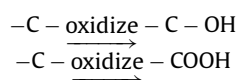


Fig. 4. FT-IR spectra of MC and COMC samples.

samples. It was mainly caused by the O–H stretching vibration of the adsorbed water molecules, which also had a bending vibration mode corresponding to the band recorded at 1600 cm^{-1} . Bands at $1600\text{--}1745\text{ cm}^{-1}$ denoted the absorption of stretching and bending vibration modes of --COOH on the surface of mesoporous carbon materials (indicated by label). In addition, the broad band that appeared at 1150 cm^{-1} was caused by the stretching vibration of C–O bonds. The relative intensity of these bands in COMC samples was higher than those of the MC sample, indicating that more oxygen-containing functional groups were introduced when the oxidation have been done [28,33–35]. This fact that oxidation caused higher content of functional groups, indicated that there were chemical reactions on the carbon surface between the nitric acid and C atoms, which were partially oxidized to form C–OH and/or --COOH . The reaction equations were proposed as follows:



3.2. Adsorption studies

3.2.1. Effect of contact time and concentration

In order to establish equilibration time for maximum uptake and to know the kinetics of adsorption process, the adsorption of naphthalene (as a one of PAHs) on mesoporous carbon adsorbent was studied as a function of contact time and results are shown in Fig. 5. It is seen that the rate of uptake of the PAHs is rapid in the beginning and 50% adsorption is completed within 2 h. Fig. 5 also indicates that the time required for equilibrium adsorption is 6 h. Thus, for all equilibrium adsorption studies, the equilibration period was kept 8 h. The effect of concentration on the equilibration time was also investigated as a function of initial naphthalene concentration and the results are shown in Fig. 6 (on COMC). It was found that time of equilibrium as well as time required to achieve a definite fraction of equilibrium adsorption is independent of initial concentration. These results indicate that the adsorption process is first order.

3.2.2. Effect of pH

The removal of a pollutant from an aqueous medium by adsorption is highly dependent on the solution pH, which affects the surface charge of the adsorbent and the degree of ionization of the adsorbate.

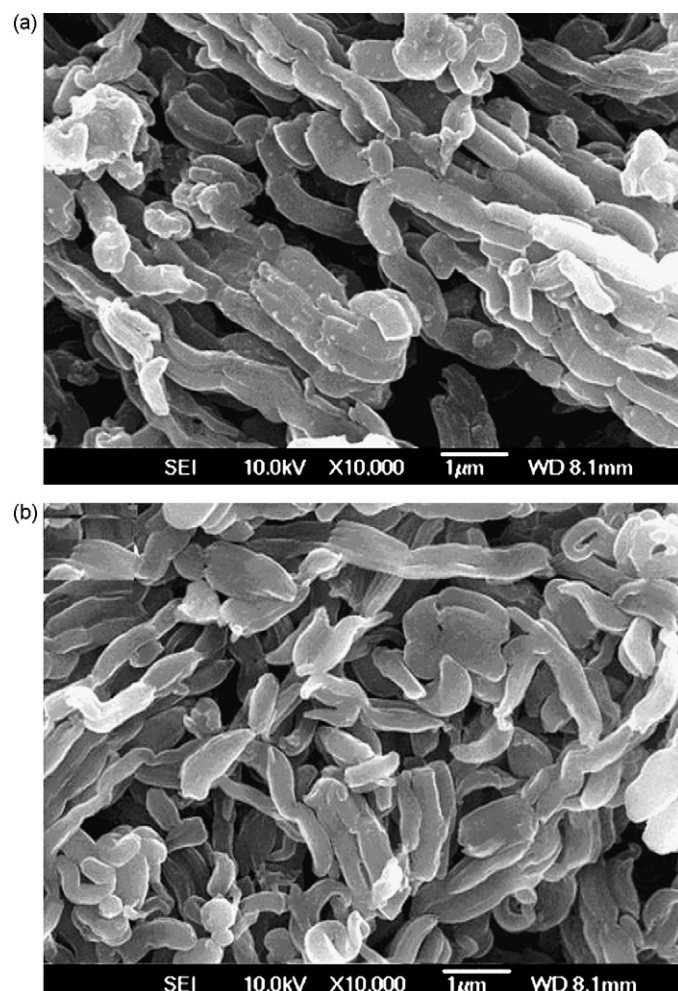


Fig. 3. SEM photographs of: (a) MC and (b) COMC.

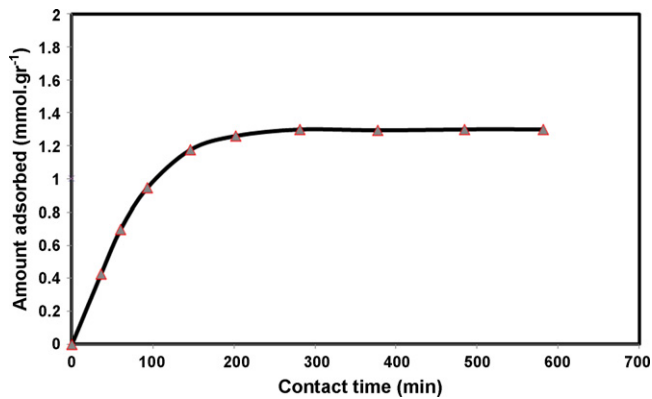


Fig. 5. Effect of contact time on removal of naphthalene ([naphthalene]=30 mg/L, agitation speed=150 (rpm), adsorbent dosage=0.2 g/L, room temperature=25 + 1 °C).

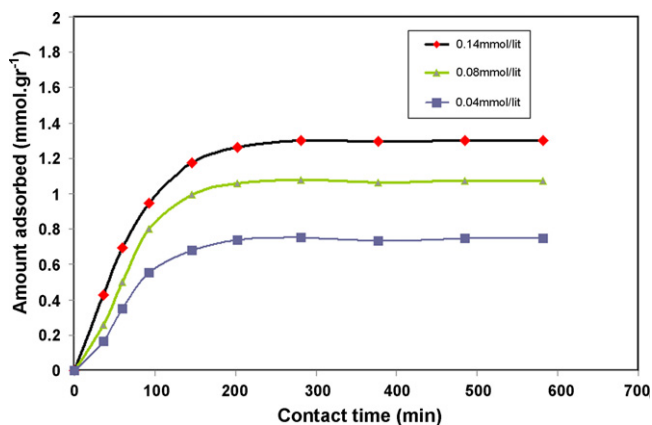


Fig. 6. Effect of initial concentration on removal of naphthalene (agitation speed = 150 (rpm), adsorbent dosage = 0.2 g/L, room temperature = 25 + 1 °C).

The effect of the pH on the adsorption of PAHs onto the COMC and MC was studied at constant initial concentration of 30 ppm PAHs and the amount of adsorbent (20 mg) at 150 rpm agitation speed and at 25 °C. The range of the pH was adjusted between 2 and 10. Figs. 7 and 8 show the effect of pH on the adsorption of PAHs onto the COMC and MC. The pH of solution appears to be a key factor affecting the adsorption characteristics of PAHs onto the carbonous adsorbent. As can be seen from Figs. 7 and 8, it

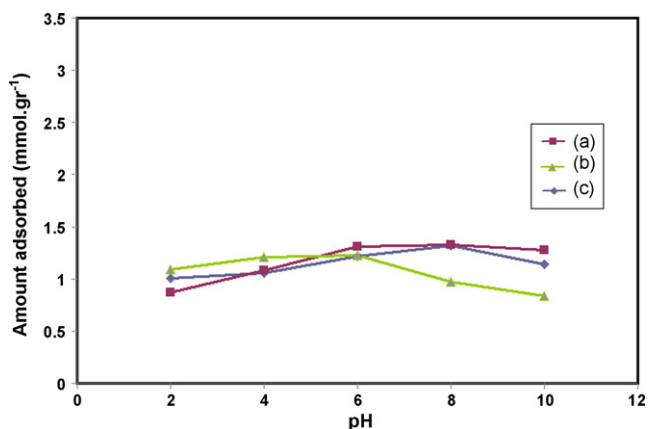


Fig. 7. Effect of pH on PAHs removal over MC as adsorbent: (a) 1-naphthol, (b) 1,5-naphthalenediamine and (c) naphthalene (adsorbent dose=0.2 g/L, agitation speed = 150 rpm, room temperature = 25 + 1 °C).

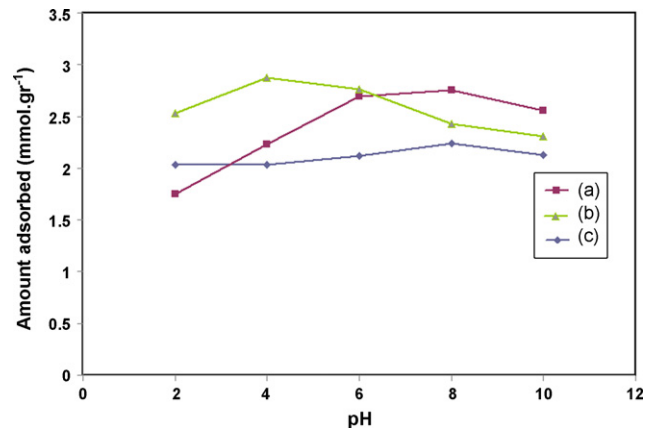


Fig. 8. Effect of pH on PAHs removal over COMC as adsorbent: (a) 1-naphthol, (b) 1,5-naphthalenediamine and (c) naphthalene (adsorbent dose=0.2 g/L, agitation speed = 150 rpm, room temperature = 25 + 1 °C).

is evident that increasing the pH of solution serves to increase the adsorption capacity with a significant enhancement in the adsorption process occurring as the pH increased from 2 to 6 for 1,5-naphthalenediamine and 2 to 8 for naphthalene and 1-naphthol. These results were obtained because of difference in functional group between 1,5-naphthalenediamine and others. Although, COMC has showed more amount of adsorption and more dependent to pH effect. The pH of solutions is one of the most important factors which affects on PAHs adsorption as it controls the electrostatic interactions between the adsorbent and the adsorbate. The surface properties of the carbon change with an increase of pH. The surface acidity of the mesoporous carbon might affect the pH of the solution for the adsorption of PAHs onto the mesoporous carbon. The amphoteric nature of carbon depends on not only the surface functional groups of the carbon but also the isoelectric point (pH_{IEP}) or point of zero charge (pH_{PZC}) of the nanoporous carbon [36]. Cationic adsorption is favored at $pH > pH_{PZC}$ (e.g., on COOH groups) and anionic adsorption is favored at $pH < pH_{PZC}$ (e.g., on Lewis-base-type basal plane sites) [36]. The percentage of adsorption increased as the pH of the solution was increased. This result might show that the zero point of charge (pH_{PZC}) for the mesoporous carbon lies between pH 3.5 and 6.5. The total or external surface charges are positive at a lower solution of pH. Thus, lower adsorption of PAHs took place at a lower solution of pH. When the pH value increased, the surface of the mesoporous carbon was negatively charged more. Thus, the adsorption of the PAHs with positive charge was reached maximum at pH 4 and 8 for 1,5-naphthalenediamine and naphthalene and 1-naphthol.

3.2.3. Effect of chemical modification

In order to evaluate the efficacy of the prepared adsorbents, the equilibrium adsorption of the PAHs was studied as a function of equilibrium concentration. The adsorption isotherms of naphthalene, 1-naphthol and 1,5-naphthalenediamine on COMC and MC are shown in Figs. 9 and 10. It is seen that order of adsorption in terms of amount adsorbed (mmol/g) on different adsorbents is: COMC > MC.

It is interesting to see that the amount of PAHs adsorbed increases with increasing solution pH for both samples. Further, COMC registers higher PAHs adsorption capacity (2.8, 2.3 and 1.6 mmol/g for 1,5-naphthalenediamine, 1-naphthol and naphthalene) than the untreated mesoporous carbon (1.1, 1.25 and 1.36 mmol/g for 1,5-naphthalenediamine, 1-naphthol and naphthalene). The higher adsorption capacity of COMC can be explained by several facts. Undoubtedly, increasing in interaction as a cause of more functional group in COMC, explained this [28,33–35]. It is

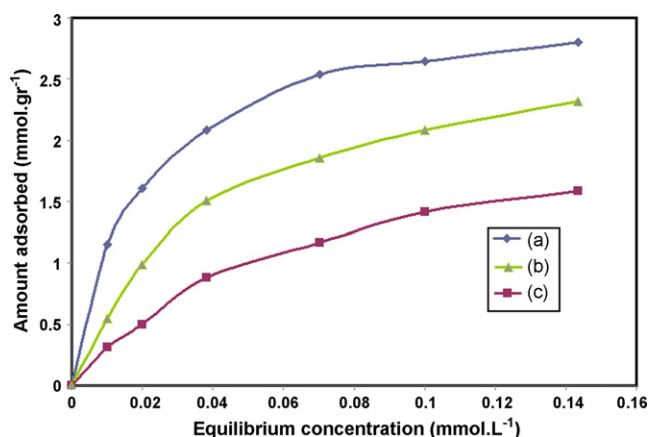


Fig. 9. Adsorption isotherm for: (a) 1,5-naphthalenediamine, (b) 1-naphthol and (c) naphthalene removal on COMC (contact time = 4 h, agitation speed = 150 (rpm), adsorbent dosage = 0.2 g/L, room temperature = 25 + 1 °C).

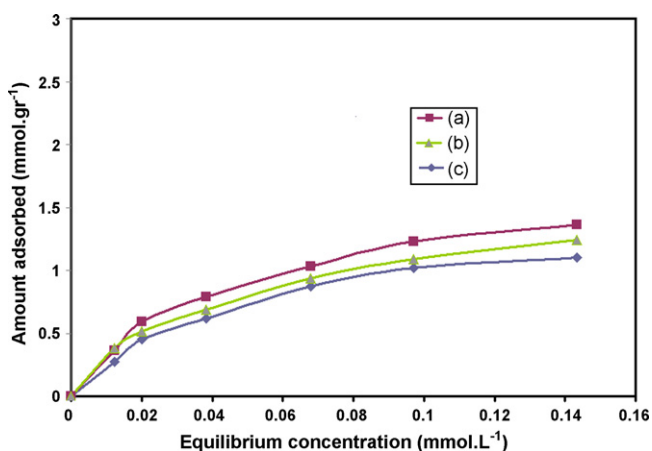


Fig. 10. Adsorption isotherm for: (a) naphthalene, (b) 1-naphthol and (c) 1,5-naphthalenediamine removal on MC (contact time = 4 h, agitation speed = 150 (rpm), adsorbent dosage = 0.2 g/L, room temperature = 25 + 1 °C).

also surmised that the anchoring ability of –COOH groups located inside and at the entrance of the mesopores might obstruct desorption of PAHs molecules from the pore channels of chemically oxidized mesoporous carbon, resulting in an increase in the PAHs adsorption capacity.

3.2.4. Langmuir and Freundlich isotherms

In order to indicate the sorption behavior and to estimate of adsorption capacity, adsorption isotherms have been studied. The adsorption processes of PAHs on COMC adsorbent were tested with Langmuir and Freundlich isotherm models. Two commonly used empirical adsorption models, Freundlich and Langmuir, which correspond to heterogeneous and homogeneous adsorbent surfaces, respectively, were employed in this study. The Freundlich model is

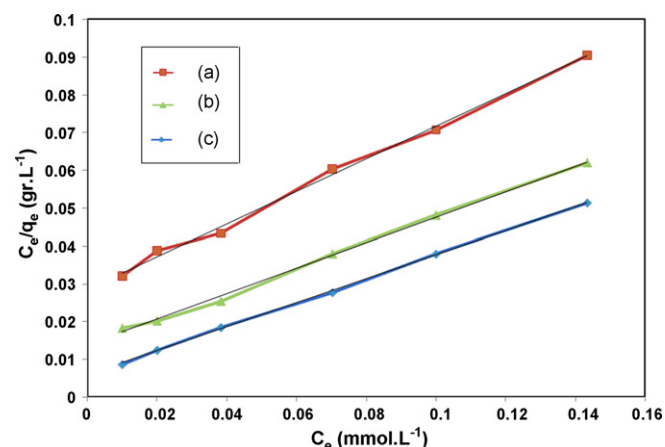


Fig. 11. Langmuir isotherm for adsorption of: (a) naphthalene, (b) 1-naphthol and (c) 1,5-naphthalenediamine on COMC.

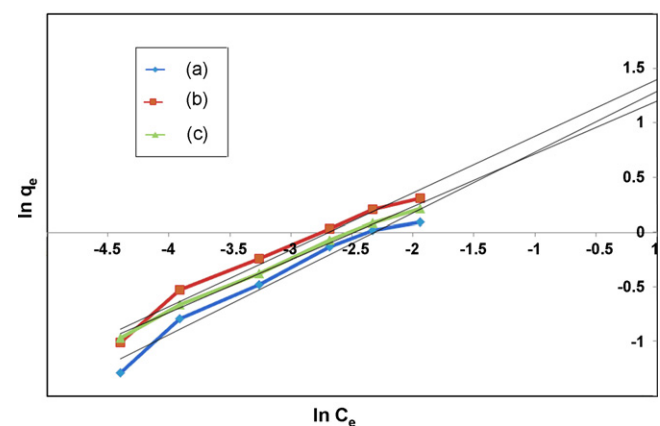


Fig. 12. Freundlich isotherm for adsorption of: (a) naphthalene, (b) 1-naphthol and (c) 1,5-naphthalenediamine on COMC.

given by the following equation:

$$\ln q_e = \ln K_f + \left(\frac{1}{n}\right) \ln C_e \quad (3)$$

where k_f and n are the Freundlich constants related to adsorption capacity and intensity, respectively. In the second model, the Langmuir equation assumes maximum adsorption occurs when the surface is covered by the adsorbate, because the number of identical sites on:

$$\frac{C_e}{q_e} = \left(\frac{1}{q_m b}\right) + \left(\frac{1}{q_m}\right) C \quad (4)$$

where q_e (mmol g^{-1}) is the amount adsorbed at equilibrium concentration C_e (mmol l^{-1}), q_m (mg g^{-1}) is the Langmuir constant representing maximum monolayer capacity and b is the Langmuir constant related to energy of adsorption.

The isotherm data has linearized using the Langmuir equation and shown in Fig. 11. The regression constants are tabulated in

Table 2
Langmuir and Freundlich constants for adsorption of PAHs on COMC.

Analyte	Langmuir			Freundlich		
	q_m (mmol/g)	b (L/mmol)	R^2	K_f (mmol/g)	n (L/mmol)	R^2
Naphthalene	2.32	15.39	0.996	5.91	1.60	0.982
1,5-Naphthalenediamine	3.17	63.2	0.999	5.81	2.99	0.965
1-Naphthol	2.98	25.85	0.997	7.23	1.89	0.955

Table 2. The high value of correlation coefficient indicated a good agreement between the parameters. The same data is also fitted by the Freundlich equation and shown in Fig. 12 and Table 2. The value of correlation coefficients showed that the data conform well to the Langmuir equation.

4. Conclusions

Liquid-phase oxidation by nitric acid was used for the surface modification of mesoporous carbon materials. The chemically oxidized mesoporous carbon prepared in this work is suitable for the adsorption of aqueous PAHs from industrial wastewater. The adsorption is more effective at pH range of 5–7. It was indicated that the surface oxygen groups of the precursor can act as 'active site', which play an important role in the adsorption process. The adsorption behavior of naphthalene on the OMC from aqueous solution shows promising. All adsorption isotherms are well predicted by Langmuir model.

Acknowledgements

Dr. S.N. Ashrafizadeh from IUST is acknowledged for his consultation during the course of this project. Dr. Garakani from Research Institute of petroleum industry is acknowledged for its assistance in conducting experiments.

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