



Preparation of carbon aerogels with different pore structures and their fixed bed adsorption properties for dye removal

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ABSTRACT

Controlled porosity carbon aerogels are prepared by a sol–gel polymerization method and the prepared materials are used as fixed bed adsorbents for dye removal. The influences of operating conditions and preparation factors on the adsorption of C. I. Reactive Red 2, as a model compound, from aqueous solution were investigated. Many column parameters were estimated at different stages and the Bed-Depth-Service-Time model was used to analyze the experimental data. The results showed that the adsorption bed capacity increased with increasing bed height, decreasing liquid flow rate and decreasing initial dye concentration. Moreover, the work indicated that the adsorption ability of the carbon aerogel could be controlled by adjusting the molar ratio of resorcinol to surfactant and carbonization conditions. In addition, the adsorption capacity could be improved when the carbon aerogel was activated by CO₂. The reasons for the difference in adsorption ability could be related to the different pore structure characteristics of various samples.

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1. Introduction

Dyes and pigments are released into wastewaters from various industries, mainly from dye production and textile finishing [1]. Many dyes and pigments are toxic in nature which can cause allergic dermatitis, skin irritation, cancer and mutation [2]. Therefore their removal from textile effluents has been the target of great attention in the last few years. Several conventional wastewater treatment technologies have been applied for dye removal, including physical, chemical and biological processing [3–5]. Reactive dyes are the most important group of dyes used in cellulose dyeing, and these highly water soluble persistent substances are difficult to eliminate by flocculation, biodegradation and many other technologies [6]. However, adsorption is one of the most effective processes for removal of color and treatment of reactive dye effluents [7,8].

Recently a new form of mesoporous carbon adsorbent-carbon aerogel has appeared. A carbon aerogel is a typical porous carbon material that has a well-defined and controlled pore structure, high surface areas and different surface chemistry [9,10]. Carbon aerogel has been reported for the adsorption of inorganic (especially metal

ions) [11,12], pharmaceuticals [13] and VOC gases [14,15], but its use for the removal of organic dyes has not been widely reported. It is therefore desirable to explore the application of treatment of reactive dye waste using aerogels as a new adsorption material. In our laboratory a series of studies have been conducted to reducing cost in the process of preparation of carbon aerogel [16,17]. When a suitable molar ratio of resorcinol to surfactant (R/C) and an appropriate resorcinol–formaldehyde concentration were selected under a fixed carbonization condition, the carbon aerogel thus obtained had a well-defined pore structure. In previous studies, we also have preliminary investigated the adsorption of a reactive dye by a carbon aerogel in batch mode as an alternative technology for dye removal from aqueous solution [18]. The results showed that carbon aerogels are effective adsorbents for the adsorption of C. I. Reactive Red 2 from aqueous solution. In this paper, controlled porosity carbon aerogels are prepared by sol–gel polymerization method and different pore structure materials are used as fixed bed adsorbents for dye removal. In order to analyze the column dynamics of prepared carbon aerogels in the sorption process, the influence of the flow rate, adsorbent bed height and the inlet dye concentration on the breakthrough curves was investigated. The Bed-Depth-Service-Time (BDST) model was used to evaluate the column capacity and performance of fixed bed, more importantly, the effect of the R/C, carbonization temperature and activation with CO₂ on the performance of fixed bed was also discussed.

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2. Experimental

2.1. Adsorbate and the preparation of adsorbents

The textile dye, reactive brilliant red X-3B (C. I. Reactive Red 2, purity of 98%), with a molar mass (g/mol) of 615 ($C_{19}H_{10}O_7N_6Cl_2S_2Na_2$) was obtained from Shanghai Dyestuffs Co., Ltd. of China. The experimental solutions of desired concentration were obtained by successive dilutions with double-distilled water.

The preparation of the carbon aerogels was carried out using a procedure based on our previous reported method [18]. Briefly, resorcinol (R), formaldehyde (F) and surfactant (C) were mixed with water (W) according to predetermined recipes (The stoichiometric R/C molar ratios were 100, 125, 200, 500 and 1000, respectively), and then transferred into a glass vial. The sealed vial was placed in a water bath at 80 °C to carry out the sol–gel polymerization. Subsequently, the sample was dried by ambient-pressure drying (48 h at room temperature, 24 h at 60 °C, and 3 h at 105 °C). Finally, the dried sample was heated to carbonization temperature with a heating rate of 5 °C/min and kept at this carbonization temperature for 3 h in flowing N_2 (800 mL/min). The carbonization temperatures were 300, 500, 700 and 900 °C, respectively. Carbon aerogel sample prepared with R/C = 125 at 900 °C, was selected to obtain activated carbon aerogel (ACA), was first heated in N_2 flow of 800 cm³/min to 900 °C, and then activated at 900 °C in mixed gas flow of CO_2 (1000 cm³/min) and N_2 (400 cm³/min) for 1 h. All samples were broken to afford material of 40–100 mesh.

For carbon aerogel samples in all experiments except for that on the effect of R/C and carbonization temperature, the R/C is 125 and the temperature is 900 °C.

2.2. Measurement of the pore parameters

Approximately 0.12 g samples were heated to 250 °C to remove all the adsorbed species. Nitrogen adsorption and desorption isotherms were then taken using an ASAP 2010 Surface Area Analyzer (Micromeritics Instrument Corp.). According to the resulting isotherms, the BET surface area (S_{BET}), micropore volume (V_{mic}), micropore surface area (S_{mic}), mesopore volume (V_{BJH}), mesopore surface area (S_{BJH}), and pore size of the samples were analyzed by BET (Brunauer–Emmett–Teller) theory, t-plot theory and BJH (Barrett–Johnner–Halendar) theory, respectively.

2.3. Adsorption experimental methods and measurements

The carbon aerogel was placed in a glass column of 300 mm length and 11 mm internal diameter which served as the fixed bed adsorbent. The adsorption process was as follows. To the bottom of the column a small glass fiber pad was inserted, an aqueous slurry of the carbon aerogel was then aspirated into the column to obtain the carbon aerogel bed. A second small glass fiber pad was used to plug the top of the sorbent bed in order to prevent the loss of the carbon aerogel. The bed was thoroughly washed with distilled water and left overnight to ensure a closely packed arrangement of adsorbent particles without voids, channels or cracks was obtained. The aqueous solution with a known dye concentration was fed to the top of the column at a desired flow rate driven by a peristaltic pump until the dye concentration of the column effluent approached 95% of the feed concentration. Samples of effluents were collected periodically and the remaining concentration was analyzed using a UV/Vis spectrophotometer at a maximum wavelength of 538 nm. Therefore, the desired breakthrough concentration (C_b) was determined at 5% of the inlet feed concentration (C_0), which is $C_t/C_0 = 0.05$, where C_t is the outlet solute concentration

(mol/L). The flow through the column was continued until the concentration of column effluent approached ~ 1 .

3. Results and discussion

3.1. Effect of operating conditions on bed performance

The efficiency of the packed bed and the shape of the concentration–time profile are very important characteristics for operation and process design of a column because they directly affect the feasibility and economics of the sorption performance [21]. There are many factors which affect column breakthrough, such as the nature of the adsorbate and adsorbent. As these factors were already fixed in this experiment, the effect of process variables on bed performance was evaluated by measurement of the breakthrough curves. Experimental determination of these parameters is dependent on column operating conditions such as flow rate, bed height and feed pollutant concentration.

Fig. 1a shows that the effect of the flow rate (0.58, 0.78 and 1.23 cm³/min) on the breakthrough curves at a constant bed depth (5.2 cm) and influent concentration (0.006 M). The breakthrough curves of the ratio between effluent and influent concentration (C_t/C_0) versus time for various bed depths at flow rate of 0.78 cm³/min and influent concentration of 0.006 M are shown in Fig. 1b. The results indicated that sorbent bed height strongly affects the treated time or throughput volume. The effect of the influent concentration (0.004, 0.006 and 0.008 M) on the breakthrough curves at a constant bed depth (5.2 cm) at flow rate (0.78 cm³/min) is compared in Fig. 1c. Basically, the curves show the same typical ‘S’ and relatively grading shape, indicating that the process requires a long time. Moreover, the break point appears faster with increasing liquid flow rate and initial dye concentration, but more slowly with increasing the bed height. This is due to the decrease in contact time between the dye and the carbon aerogel. Decrease of the contact time will result in premature breakthrough to occur, thus reducing the service time of the bed [19].

Several bed parameters are important for the characterization of any adsorption process. They were determined for each column from the breakthrough curves using previously published calculation methods [20–22]. Amongst these properties the following stand out: (1) time to reach different stages (at breakthrough point, t_b , at 0.5 and 0.9 loading, $t_{0.5}$ and t_e (taken as exhaustion points)); (2) volume of effluent treated at previous stages (V_b , $V_{0.5}$ and V_e); (3) dye removal at the previous stages, $Removal_b\%$, $Removal_{0.5}\%$ and $Removal_e\%$; (4) amounts of dye adsorbed at the previous stages, X_b , $X_{0.5}$ and X_e ; (5) the height of mass transfer zone (H_{MTZ}); (6) the rate of adsorption capacity in the batch system to adsorption capacity in the column system ($q_e(\text{column})/q_e(\text{batch})$).

The values of the performance parameters for flow rate, adsorbent bed height and the initial dye concentration were calculated and are shown in Table 1. It was shown that the breakthrough service time (t_b , $t_{0.5}$ and t_e) and volume of effluent treated at different stages (V_b , $V_{0.5}$ and V_e) increased with the decreasing of initial feed dye concentration and inlet flow rate, but it increased with the bed height. Moreover, the dye removal and the amounts of dye adsorbed at various stages, X_b , $X_{0.5}$ and X_e for all samples enhanced with prolonging breakthrough time t . At the same processing time, the dye removal and the amounts of dye adsorbed decreased with increasing inlet dye concentration and flow rate, but increased with decreasing bed height. The results indicated the adsorption capacity of the carbon aerogel increased with decreasing initial feed dye concentration and inlet flow rate, but decreased with increasing bed height. From Table 1, it also can be seen that the height of the mass transfer zone (H_{MTZ}) reduced with

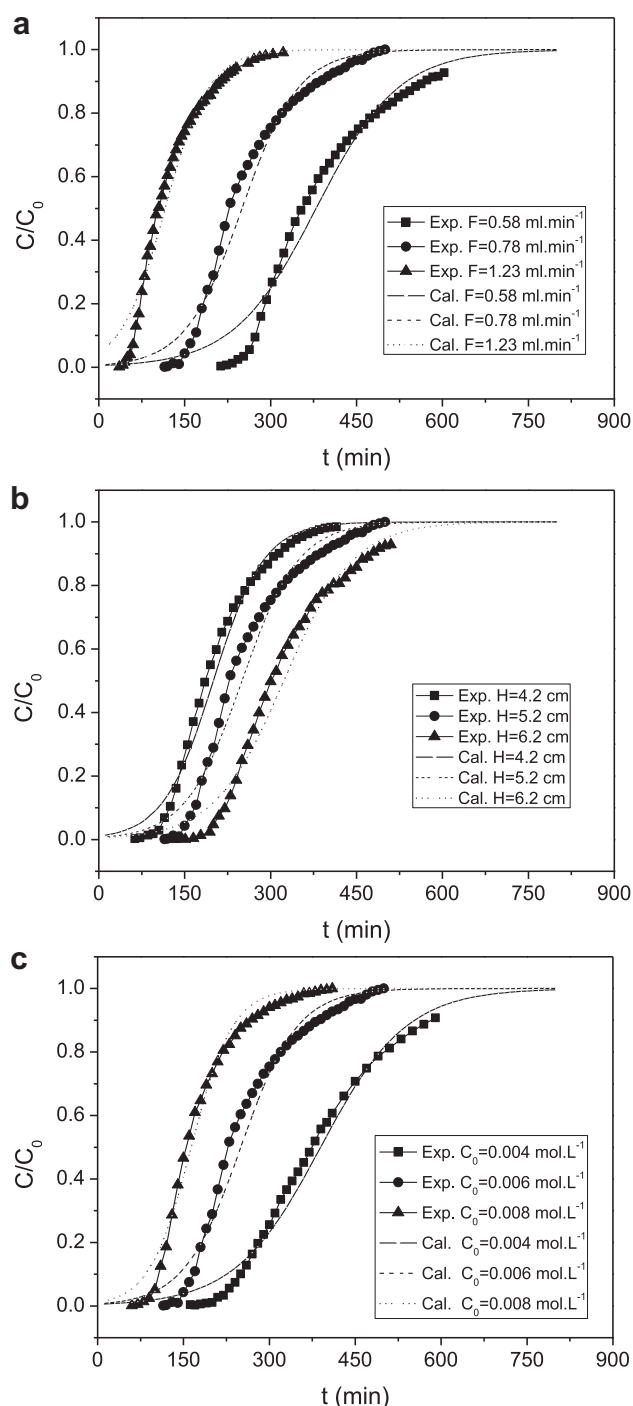


Fig. 1. The breakthrough curves for adsorption of reactive dye onto carbon aerogel at different flow rates (a), bed heights (b) and feed dye concentrations (c).

increasing of bed height but increased with increasing inlet dye concentration and flow rate. In addition, the rate of adsorption capacity in a batch system to adsorption capacity in the column system ($q_e(\text{column})/q_e(\text{batch})$) of all samples below unit, and increased with decreasing of inlet flow rate and dye concentration, but decreased with decreasing of bed height. The value of q_e obtained in this study was slightly inferior to those obtained in batch system, it can be deduced that the breakthrough is reached before all the active sites of the carbon aerogel are occupied by the dye molecules.

3.2. Effect of preparation factors on bed performance

The previous study showed that the pore structure and pore size distribution of carbon aerogel (CA) could be controlled through adjusting R/C [10]. We can obtain the CA samples with different BET specific surface areas, pore size distribution and pore shapes through adjustment the ratio of R/C during their synthesis. In this experiment, five ratios of R/C we chosen were 100, 125, 200, 500, and 1000, respectively. The effect of the R/C on the breakthrough curves at a constant bed depth (5.2 cm), inlet concentration (0.006 M) and flow rate (0.78 cm^3/min) are compared in Fig. 2a. From the obtained breakthrough curves (Fig. 2a), S shaped forms are exhibited but with different degrees and trends. The degree of steepness of the breakthrough curve increased with the increase of R/C. Many performance parameters of fixed beds with different R/C samples obtained from breakthrough curves are listed in Table 2. It can be seen that the maximum service time and volume of effluent treated at different stages (t_b , $t_{0.5}$, t_e , V_b , $V_{0.5}$ and V_e) occurred at different samples. The dye removal of all samples decreased with increasing service time, but the value of dye removal at same service time increased with increasing the ratio of R/C. It is evident that the maximum of X_b and $X_{0.5}$ for the five samples is observed at R/C = 200 but X_e is observed at R/C = 125. All of these data reflected that different R/C samples have different adsorption capacity and adsorption rate. The adsorption capacity of carbon aerogel with R/C = 125 is a maximum at T_e .

The breakthrough curves were obtained as service time versus normalized dye concentration (C/C_0) for different samples under various carbonization temperatures are presented in Fig. 2b. Evidently, all breakthrough curves correspond to the 'logistic curve', and the degree of steepness decreased with increasing carbonization temperature of samples. The several performance parameters based on this work are listed in Table 2. Upon considering the increased carbonization temperature (from 300 °C to 700 °C), there is a clear trend of improved performance as evident from all the bed characteristics (Table 2). Therefore, there is a one direction increase in volumes treated, service time, dye removal percent, weight uptake duration to reach specific loadings, in addition to the service time, and decrease in H_{MTZ} .

The effect on adsorption property of activated carbon aerogel can be seen from Fig. 2b and Table 2. From these curves and data, it can be seen that adsorption capacity of activated carbon aerogel is larger than that of inactivated carbon aerogel bed. Besides, the service time t for the CO_2 activated carbon aerogel is longer than that of inactivated carbon aerogel.

3.3. Analysis and evaluating of column data with BDST model

Adsorption operation is a complex process and its performance is governed by many variables [23]. In conducting packed-bed sorption experiments, normally the results are presented in terms of concentration–time profile or breakthrough curve. From such results, the parameters stated in the previous section can be obtained by calculation. The process of calculation is complicated and time consuming. Prediction of the adsorption rate and the maximum sorption bed capacity can be determined by applying certain mathematical models. Among various models, the simplest model, known as the BDST is widely used. The BDST model has also been successfully used in describing and predicting dye column adsorption using various adsorbents [24,25].

The BDST model proposed by Bohart and Adams (1920) [26] and later linearized by Hutchins (1973) [27] has been reported by McKay and Bino. (1990) [28] as offering the simplest approach and most rapid prediction of adsorption performance. The model gives a linear relationship between the time required to reach the desired

Table 1

Fixed bed performance parameters in the adsorption of C. I. Reactive Red 2 at various operating conditions.

Parameters	$C_0 = 0.004 \text{ M}$		$C_0 = 0.006 \text{ M}$			$C_0 = 0.008 \text{ M}$	
	$F = 0.78 \text{ cm}^3/\text{min}$		$F = 0.58 \text{ cm}^3/\text{min}$		$F = 0.78 \text{ cm}^3/\text{min}$	$F = 1.23 \text{ cm}^3/\text{min}$	
	$H = 5.2 \text{ cm}$		$H = 5.2 \text{ cm}$		$H = 4.2 \text{ cm}$	$H = 5.2 \text{ cm}$	$H = 5.2 \text{ cm}$
V_b (ml)	176.3		150.2		86.6	117.8	158.3
$V_{0.5}$ (ml)	286.3		206.5		145.1	177.8	238.7
V_e (ml)	452.4		329.4		241.8	301.9	374.4
t_b (min)	226		259		111	151	203
$t_{0.5}$ (min)	367		356		186	228	306
t_e (min)	580		568		310	387	480
Removal _b %	99.6		99.5		94.1	99.4	99.6
Removal _{0.5} %	91.2		91.4		89.1	90.9	91.2
Removal _e %	66.8		67.8		63.7	64.2	66.7
X_b (mg/g)	287.8		368.3		250.1	286.9	323.3
$X_{0.5}$ (mg/g)	428.0		467.9		396.7	398.4	446.3
X_e (mg/g)	495.9		547.0		473.1	476.5	512.0
H_{MTZ} (cm)	4.74		4.18		5.07	4.91	4.49
$q_e(\text{col})/q_e(\text{bat})$	0.878		0.968		0.837	0.843	0.906
							0.629
							0.757

breakthrough concentration and the weight of adsorbent used (W). The equation can be represented as follows:

$$\ln\left(\frac{C_0 - C_t}{C_t}\right) = \ln\left[\exp\left(\frac{k_1 Q_e W}{F}\right) - 1\right] - k_1 C_0 t \quad (1)$$

where k_1 is the adsorption rate constant ($\text{L}/(\text{mol min})$), Q_e is the capacity for a given bed (mol/g), F is the flow rate (L/min), t is the

service time (min), and W is the weight of adsorbent used (g). Because the exponential term is usually much larger than unity, the unity term in the brackets in the right-hand side of Eq. (1) is often neglected [24], leaving

$$\ln\left(\frac{C_0}{C_t} - 1\right) = \frac{k_1 Q_e W}{F} - k_1 C_0 t \quad (2)$$

The two model parameters, Q_e and k_1 , are normally obtained from the intercept and slope in the plot of $\ln[C_t/(C_0 - C_t)]$ versus t according to Eq. (2). The BDST model was used to analyze the experimental data and the calculated values of Q_e and k_1 listed in Figs. 1 and 2 and Tables 3–5. Tables 3–5 shows the correlation coefficients (R^2) are higher than 0.93. Thus, Eq. (2) is satisfactorily with the experimental data and indicating the validity of this model. Moreover, it is found that the rules of adsorption capacity and adsorption rate are the same for different samples with two methods by comparing Tables 3–5 and Tables 1 and 2.

From Table 3, it is evident that adsorption capacity (Q_e) decreased and adsorption rate constant (k_1) increased with increasing liquid flow rate (F). In general, a higher flow rate does decrease the external mass transfer resistance around the surface of adsorbents. At the same time, the residence time of solution within the bed is decreased. Then, the dye molecules have less time to penetrate and diffuse into the center of the adsorbent [29]. Thereby, decreasing mass transfer resistance results in an increase of the adsorption rate constant (k_1). The adsorption capacity (Q_e) decreased with increasing flow rates on account of the shorter residence times.

Similarly, as the bed depth increases, the residence time of the fluid inside the column increases, allowing the dye molecules to diffuse deeper inside the adsorbent. Thus, the bed capacity (Q_e) will increase with the increase in the service time. Also the residence time would be increased with the adsorption bed capacity increasing, thus the adsorption rate constant (k_1) would be decreased.

As regards the inlet dye concentration, a high dye concentration provides a high driving force for the adsorption process [30]. The driving force for adsorption is the concentration difference between the dye on the carbon aerogel and in the solution. Thus the high driving force would result in better column performance. However, On the other hand, an increase in the inlet concentration diminished the breakthrough time, due to the dye concentration which saturated the carbon aerogel more quickly. So the residence time of the fluid inside the column decreases. This would reduce intra-particle diffusion and decrease adsorption bed capacity.

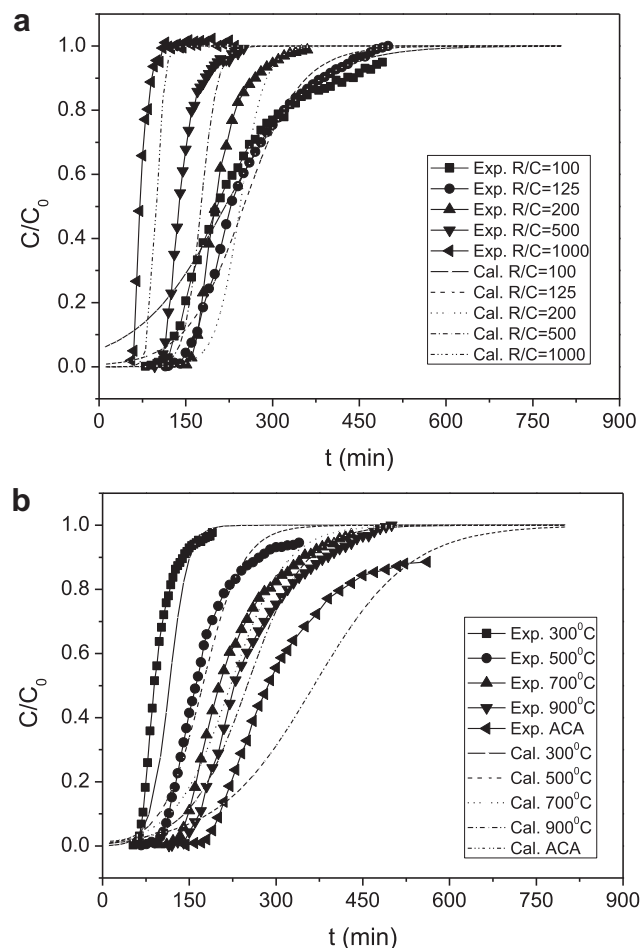


Fig. 2. The breakthrough curves for adsorption of reactive dye onto carbon aerogel with different R/C (a) and undergoing different carbonization process (b).

Table 2

Fixed bed performance parameters in the adsorption of C. I. Reactive Red 2 using different carbon aerogel samples.

Sample	R/C = 100 T = 900 °C	R/C = 125 T = 900 °C	R/C = 200 T = 900 °C	R/C = 500 T = 900 °C	R/C = 1000 T = 900 °C	R/C = 125 T = 700 °C	R/C = 125 T = 500 °C	R/C = 125 T = 300 °C	ACA
V_b (ml)	97.5	117.8	126.4	85.8	46.0	106.9	81.9	50.7	148.2
$V_{0.5}$ (ml)	159.1	177.8	155.2	107.6	53.8	157.6	125.6	68.6	223.1
V_{ex} (ml)	333.1	301.9	210.6	143.5	70.2	272.2	210.6	106.9	466.4
t_b (min)	125	151	162	110	59	137	105	65	190
$t_{0.5}$ (min)	204	228	199	138	69	202	161	88	286
t_{ex} (min)	427	387	270	184	90	349	270	137	598
Removal _b %	99.4	99.4	99.8	99.8	99.8	99.6	99.4	99.8	99.6
Removal _{0.5} %	88.4	90.9	94.3	94.9	96.6	91.2	90.5	93.5	90.5
Removal _{ex} %	54.6	64.2	76.6	77.2	80.6	63.2	63.3	69.2	54.4
X_b (mg/g)	230.8	286.9	361.0	261.0	149.7	261.7	203.0	149.7	417.0
$X_{0.5}$ (mg/g)	335.0	398.4	423.2	311.5	169.6	353.3	283.4	189.9	570.2
X_{ex} (mg/g)	433.2	476.5	461.6	337.8	184.5	423.0	332.4	218.7	716.4
H_{MTZ} (cm)	6.71	4.91	2.71	2.70	2.22	4.99	5.00	3.95	6.51

Table 2 showed that adsorption bed capacity decreased but rate constant slightly increased with increasing inlet dye concentration. This again confirms that the residence time effect is more dominant in these fixed beds, as has been indicated previously.

Tables 4 and 5 list the calculated values of the capacity and adsorption rate constant k_1 for a given bed with different samples from BDST models. There is the same trend through method of both calculated and BDST model. The following section discusses the relationship between adsorption ability and pore structure of the different samples with different R/C and carbonization condition.

3.4. The relationship between adsorption ability and pore structure

As is well known, the adsorption ability of a sorbent is dominated by the pore structure and the physico-chemical nature of the solid surface. From Table 4, it is found that the adsorption rate increases with the increased R/C, but the adsorption bed capacity has a maximum adsorption. The maximum adsorption of the carbon aerogel is observed at R/C = 125. The reason of difference in adsorption ability in a fixed bed can be related to the different pore structure characteristics of various samples. The textual characteristics of the representative samples are shown in Table 4. From Tables 2 and 4, it can be concluded that the mesopore surface area and the mesopore volume of carbon aerogel play a main role on the adsorption capacity of carbon aerogel samples. However, the adsorption rate related to the volume of macropores and mesopores. In our previous study [10], it was shown that the network particle size increases with an increase of R/C. When R/C = 1000, an aerogel network with nano particles with a 100–300 nm size could be obtained. When R/C = 125, an aerogel network with nano particles of about 20 nm could be obtained. Therefore, it can be regarded that the average pore diameter of macropores and mesopores derived from space between carbons particles increased with increasing R/C of samples. The adsorption rate depended on the pores diameter and volume of macropore and mesopore. So the

adsorption rate constant increased with increasing R/C. From Table 4, it also can be found that the value of adsorption rate constant of samples with R/C = 1000 is about 11.5 times than that of samples with R/C = 100.

Such a trend could be associated with relative increase in surface area as noticed from Table 5. From Table 5, it is found that the adsorption rate increases as carbonization temperature decreased and the adsorption bed capacity increases as carbonization temperature increased. According to the data list of Table 5, it can be concluded that micropore surface area and micropore volume of carbon aerogel also play a main role on the adsorption capacity of carbon aerogel samples. It is noticeable that the sample heat treated at 900 °C presents an odd exceptional case such that we represent the order of efficiency of dye adsorption according to the surface area. The phenomena gives information that the adsorption capacity is not only related to surface area but also related to surface chemical property of samples.

From Table 5, it can also be seen that adsorption capacity of activated carbon aerogel is larger than that of inactivated carbon aerogel bed. Besides, the k value for CO₂ activated carbon aerogel is smaller than that of inactivated carbon aerogel. Actually, the adsorption capacity and adsorption rate constant of the activated carbon aerogel determined by BDST models are 1.14 mol/g and 2.012 L/(mol min), respectively. Whereas the adsorption capacity and adsorption rate constant of the inactivated carbon aerogel are 0.78 mol/g and 3.373 L/(mol min). It could be inferred that the pore structure of the carbon aerogel is changed during the CO₂ activation process. Also the activation would lead to an apparent increase in micropore volume/surface area and a slight increase in mesopore volume than carbon aerogel, which is supported by higher specific surface area, higher micropore volume and larger adsorption capacity and a smaller adsorption rate.

On the basis of the points mentioned above, it can conclude that both micropores and mesopores of carbon aerogel have an

Table 3

Model parameters for the adsorption of C. I. Reactive Red 2 using carbon aerogel at various operating conditions.

Flow rate (cm ³ /min)	Bed height (cm)	C_0 (M)	Q_e (mol/g)	k_1 (L/(mol min))	R^2
0.58	5.2	0.006	0.88	2.317	0.963
0.78	4.2	0.006	0.76	3.800	0.978
	5.2	0.006	0.78	3.373	0.969
	6.2	0.006	0.84	2.748	0.974
	5.2	0.004	0.81	3.350	0.982
	5.2	0.008	0.68	3.445	0.985
1.23	5.2	0.006	0.57	4.348	0.964

Table 4

Model parameters for the adsorptions of C. I. Reactive Red 2 and the pore structure parameters of carbon aerogel with different R/C.

R/C	CA-100	CA-125	CA-200	CA-500	CA-1000
Q_e (mol/g)	0.68	0.78	0.76	0.55	0.31
k_1 (L/(mol min))	2.183	3.373	7.942	11.870	25.240
R^2	0.957	0.969	0.958	0.973	0.952
S_{BET} (m ² g ⁻¹)	587.8	582.7	596.9	557.7	531.6
S_{micro} (m ² g ⁻¹)	321.9	312.8	361.8	395.4	438.4
S_{BJH} (m ² g ⁻¹)	265.9	269.9	257.2	164.4	84.2
V_{micro} (cm ³ g ⁻¹)	0.150	0.145	0.168	0.185	0.206
V_{BJH} (cm ³ g ⁻¹)	0.938	1.150	1.246	0.547	0.153
A.P.D _{BJH} (Å)	126.5	152.3	193.7	133.0	72.7

Table 5

Model parameters for the adsorptions of C. I. Reactive Red 2 and the pore structure parameters of carbon aerogel with different carbonization condition.

Carbonization temperature	CA-125-300	CA-125-500	CA-125-700	CA-125-900	ACA
Q_e (mol/g)	0.36	0.54	0.69	0.78	1.14
k_1 (L/(mol min))	10.378	4.85	3.497	3.373	2.012
R^2	0.968	0.968	0.956	0.969	0.936
S_{BET} ($m^2 g^{-1}$)	311.1	581.4	600.6	582.7	851.7
S_{micro} ($m^2 g^{-1}$)	42.4	282.7	331.4	312.8	560.7
S_{BJH} ($m^2 g^{-1}$)	280.4	312.2	292.5	269.9	328.2
V_{micro} ($cm^3 g^{-1}$)	0.016	0.130	0.154	0.145	0.261
V_{BJH} ($cm^3 g^{-1}$)	0.763	1.069	1.108	1.150	1.166
A.P.D _{BJH} (Å)	108.9	136.9	151.6	152.3	142.1

important contribution on the adsorption of C. I. Reactive Red 2 from water onto carbon aerogel in fixed beds.

4. Conclusions

Fixed-bed adsorption of C. I. Reactive Red 2 dye from aqueous solutions using a carbon aerogel was influenced by the adsorption operating conditions and preparation factors of the carbon aerogel adsorbent. Analyses of calculations and the BDST model all showed that adsorption capacity increased with increasing sorbent bed height but decreased with liquid flow rate and initial dye concentration. However, the reverse trend was found for the values of adsorption rate. Moreover, the adsorption ability of carbon aerogels could be controlled through adjusting R/C and carbonization conditions. Maximum adsorption capacity of carbon aerogel was observed at R/C = 125 for different R/C samples and the adsorption bed capacity increases as carbonization temperature increased. At the same time, the adsorption rate increased with increasing R/C and decreasing with the carbonization temperature. In addition, the adsorption bed capacity of C. I. Reactive Red 2 onto carbon aerogel could be improved when the carbon aerogel was activated by CO₂. Actually, the adsorption capacity and adsorption rate constant of the activated carbon aerogel determined by BDST models are 1.14 mol/g and 2.012 L/(mol min), respectively. The relationship between the adsorption behavior and pore structure parameters of carbon aerogels supported that both micropores and mesopores of the carbon aerogel make an important contribution on the adsorption capacity of C. I. Reactive Red 2 from water onto the carbon aerogel in fixed beds. More mesopores can lead to higher adsorption rate.

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