

PROPERTIES AND THERMODYNAMICS OF ADSORPTION OF BENZOIC ACID ONTO XAD-4 AND A WATER-COMPATIBLE HYPERCROSSLINKED ADSORBENT*

Fu-qiang Liu**, Jin-long Chen, Ai-min Li, Zheng-hao Fei, Zhao-lian Zhu and Quan-xing Zhang
State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing 210093, China

Abstract The adsorption behavior of benzoic acid onto a water-compatible hypercrosslinked polymeric adsorbent NJ-8 was compared with that onto macroporous Amberlite XAD-4. This paper focuses on the static equilibrium adsorption behaviors, the adsorption thermodynamics and the column dynamic adsorption profiles. Five isotherm models are used to fit the results. This shows that the Freundlich equation can give a perfect fit. The specific surface area of NJ-8 is about as high as that of Amberlite XAD-4, but the adsorbing capacity for benzoic acid on NJ-8 is about 14.9%–64.8% higher than that on Amberlite XAD-4, which is attributed to its microporous mechanism and partial polarity. The negative values of the adsorption enthalpy are indicative of an exothermic process. Both enthalpy and free energy changes of adsorption manifest a physical sorption process. The negative values of the adsorption entropy indicate that adsorption is well consistent with the restricted mobilities and the configurations of the adsorbed molecules on the surface of the studied adsorbents with superficial heterogeneity. Both adsorbents were used in mini-column experiments to demonstrate the higher breakthrough adsorbing capacity of the hypercrosslinked polymeric adsorbent NJ-8 to benzoic acid, as compared with that of Amberlite XAD-4.

Keywords Hypercrosslinked polymeric adsorbent, Benzoic acid, Adsorption behaviors, Thermodynamic properties, Mini-column adsorption

INTRODUCTION

As the chemical industries developed rapidly, serious pollution was increasingly produced, and hence did much harm to public health and the environment. Presently, various methods to treat wastewater have been developed such as wetting oxidation, extraction, membrane separation, biological degradation and adsorption. Due to the high concentrating ability of typical adsorbents, adsorption has proved to be one of the most attractive and effective techniques for purification and separation in wastewater treatment^[1–3]. Activated carbon is a porous material with a large specific surface area containing predominantly micropores, and has been widely used in industrial sorptive processes of great efficiency. However, it is not without problems. As a result research into special adsorbents has been encouraged^[4–6]. In recent years, polymeric adsorbents have increasingly been viewed as an alternative to activated carbons for the efficient removal of specific organics from contaminated water^[7–9]. Amberlite XAD-4 polymeric adsorbent with high specific surface area^[10], as widely reported, has proved to be one of the most efficient polymeric adsorbents to remove phenolic compounds from aqueous streams^[11, 12] because it is chemically stable, insoluble in solvents and more selective for aromatic solutes due to its inherent hydrophobic chemical structure. However, it has two apparent drawbacks limiting its broad application in chemical wastewater treatment, one of which is its poor affinity toward aqueous solutions and the other is its low

* This work was supported by the National Natural Science Foundation (No. 20274017) and the Science & Technology Council, of Jiangsu Province, China. Thanks also go to the Analytical Center at Jiangsu Institute of Petro-Chemical Technology for the measurement of surface area and pore diameter.

** Corresponding author: Fu-qiang Liu (刘福强), E-mail: jogia@sohu.com

Received April 15, 2002; Revised July 5, 2002; Accepted July 15, 2002

adsorbing capacity and selectivity. Thus, during the pretreatment process, some activation solvents, such as methanol, acetone or acetonitrile, have to be used to enhance the surface affinity between adsorbent and adsorbate.

Advances in polymer science have provided the opportunity to produce adsorbents of well-controlled chemistries with high specific surface area^[13–15]. To improve the performances of polymeric adsorbents, Davankov described a new series of hypercrosslinked polymeric networks^[16, 17]. This technique yielded polystyrene adsorbents of unusual hypercrosslinked structure and exceptionally high adsorbing capacity^[18, 19]. Based on the above hypercrosslinked networks, a water-compatible modified polymeric adsorbent NJ-8 was synthesized through introducing hydrophilic groups onto the surface of hypercrosslinked polymeric adsorbent during the postcrosslinking process. The use of some hypercrosslinked adsorbents has been investigated for the adsorption of organic compounds such as synthetic organic dyes, *n*-valeric acid, phenol, chlorophenol, *etc.*^[18, 20]. However, only a few insights seem to be available into the adsorption of benzoic acid on macroporous polymers or activated carbons from aqueous solutions^[7, 21]. Benzoic acid is well-known to have been widely used as a preservative or reaction intermediate, furthermore wastewater containing benzoic acid has many harmful effects on receiving water bodies if it is not treated before discharging^[22]. Consequently, the focus of this study is on the results of the static equilibrium adsorption of benzoic acid from aqueous solutions by Amberlite XAD-4 and NJ-8, and also on the values of the adsorption enthalpy, entropy and free energy. The equilibrium adsorption data were fitted by several isotherms and the results were investigated. Through mini-column experiments, the sorptive profiles and the desorptive conditions for benzoic acid were discussed and compared.

EXPERIMENTAL

Materials and Methods

Adsorbents

The spherical Amberlite XAD-4 adsorbent was purchased from Rohm-Haas Co. (Philadelphia, USA). The hypercrosslinked polymeric adsorbent NJ-8 was prepared through the following post-crosslinking step: In a 1000 mL round-bottomed flask, about 67 g chloromethylated poly(styrene-*co*-divinylbenzene) beads (chlorine content = 19.5%; crosslinking degree = 6%) were swollen in 400 mL of nitrobenzene. Under mechanical stirring, 7 g zinc chloride was added slowly at 25 °C, the mixture was further stirred at 115 °C for 12 h. Finally, the mixture was poured into an acetone bath containing 1% hydrochloric acid. Before experimentation, all used adsorbents were washed with acetone several times to remove preservation agents and polymerization residues, then dried in an oven at 60 °C for more than 8 h; finally they were stored in a desiccator overnight.

Adsorbate

The aqueous solutions were prepared by dissolving benzoic acid (A.R) in deionized water.

Characterization of adsorbents

The specific surface area and the pore distribution of the adsorbents were measured by the nitrogen adsorption and desorption method using a Micrometrics ASAP-2010 automatic surface area analysis instrument (Micromeritics Instrument, Norcross, USA). Their main characteristics are listed in Table 1. Hypercrosslinking prevents collapse of the expanded network after the removal of solvent, resulting in the creation of an extensive micropore network. Furthermore, the surface of NJ-8 polymeric adsorbent is complex and has abundant polar groups.

Static Adsorption Experiment

A bottle point isotherm procedure was used to conduct all equilibrium studies. 0.1 g Amberlite XAD-4 was rehydrated by being soaked in 0.5 mL methanol and then being thoroughly rinsed with deionized water more than 3 times; 0.1 g NJ-8 was directly weighed accurately. The adsorbents were contacted, in 250 mL stoppered conical flasks, with 100 mL of benzoic acid solution of certain concentration (*c*, mg/L) ranging from 50 to 500 mg/L. The flasks were completely sealed and then placed in an incubator shaker at three temperatures

(291 K, 305 K and 319 K) until equilibrium was achieved. The residual aqueous phase concentration (c_e , mg/L) was determined using High Performance Liquid Chromatography (HPLC) on a set-up comprising a Waters 600 controller, a Waters 600 pump and a Waters 2487 Dual Absorbance Detector (Waters Assoc., USA). Thus the adsorbent-phase solute concentration, q_e (mmol/g), is calculated by Eq. (1)

$$q_e = \frac{V(c - c_e)}{M_w} \tag{1}$$

where V is the volume of solution (L), W is the weight of dry resin (g), and M is the molecular weight of benzoic acid (122.12).

Table 1. Typical properties of the studied adsorbents

Olymeric resins	Amberlite XAD-4 ^a	NJ-8
Polarity	Nonpolar	Moderate polar
BET specific surface area (m ² /g)	880	906
Average diameter (nm)	5.8	2.5
Particle size (mm)	0.4–0.6	0.4–0.6
Pore volume (mL/g)	1.05	0.52
Micropore area (m ² /g)	3.1	529.0
Residual chloride content (%)		3.5
Oxygen content (%)		5.95
Colour	White	Deep brown

^a Measured in our work, and some differences seen elsewhere (Kunin, 1976; Azanova and Hradil, 1999)

Mini-column Adsorption Experiment

After wetting with deionized water, about 1.6 mL of the wet adsorbent was loaded into a mini-column (100 mm × 4.6 mm I.D.). The feed concentration of benzoic acid solution was kept constant (16.39 mmol/L) throughout the experiments. Benzoic acid solution was continuously passed through the adsorbent bed using a reciprocating pump until the concentration of the effluent was very close to that of the feed at room temperature. The flow rate of the solution flowing through the column for each experiment was kept at 6 BV/h. The effluents from the column were directly analyzed quantitatively by HPLC after every 5 min and they were also collected to evaluate the adsorption amounts at definite breakthrough levels following Eq. (2):

$$q_e' = \frac{V(c_i - c_o)}{V'} \tag{2}$$

where c_i is the concentration of initial solution (mmol/L), c_o is the average concentration of outflow (mmol/L), V is the volume of solution (L), V' is the volume of wet resin (L).

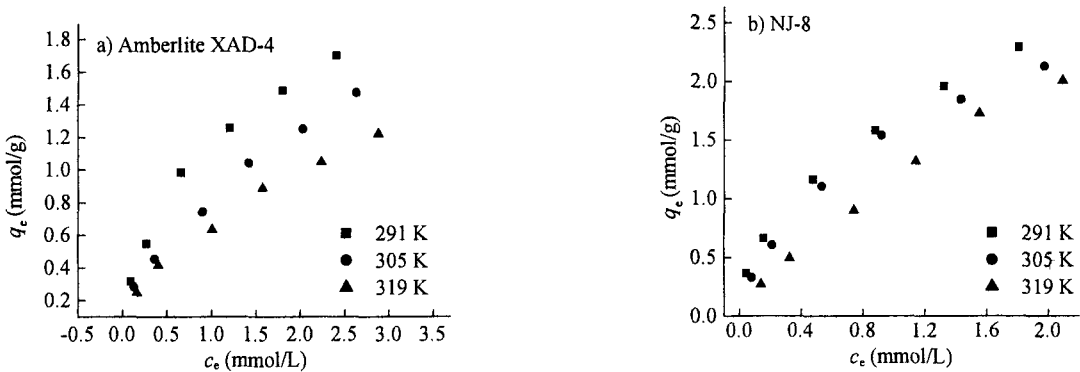


Fig. 1 Equilibrium adsorption isotherms of benzoic acid on (a) Amberlite XAD-4 and (b) NJ-8

Static Equilibrium Adsorption

Equilibrium data concerning the adsorption of benzoic acid from aqueous solutions onto both adsorbents were presented in Figs. 1(a–b). Favorable adsorption isotherms were obtained in all cases. A decreasing adsorption amount with increasing temperature is also evident. The curves corresponding to higher temperatures lie below those corresponding to lower temperatures, which indicates that adsorbents have higher adsorption amounts at a lower temperature, as reported earlier by Juang et al.^[12].

And it could be obviously noted that NJ-8 has a higher adsorbing capacity for benzoic acid than Amberlite XAD-4 as shown in Fig. 2.

As shown in Fig. 2, the yield in elimination at lower benzoic acid concentration (0.41 mmol/L at 291 K) was 77.6% using Amberlite XAD-4 versus 89.2%, obtained by NJ-8 in the same conditions. However at higher benzoic acid concentration (4.10 mmol/L at 319 K), yields in elimination using Amberlite XAD-4 and NJ-8 were 29.8% and 49.1%, respectively. Thus it is fairly rational that the adsorbing capacity of benzoic acid onto NJ-8 is as about 114.9%–164.8% higher than that on Amberlite XAD-4 in our studied range.

Numerous models have been proposed to describe adsorption isotherm relationships with different degrees of satisfaction^[23–25]. Five models were here applied to fit the experimental data. The mathematical equations, number of fitting parameters and asymptotic properties of these equations are listed in Table 2.

Table 2. Characteristics of the used isotherm models

Isotherm	Equation	Adjustable parameters	Asymptotic properties	
			Lineal at $c_e \rightarrow 0$	Adsorption maximum at $c_e \rightarrow \infty$
Linear	$q_e = Kc_e$	1	Yes	No
Langmuir	$q_e = KMc_e/(1 + Kc_e)$	2	Yes	Yes = M
Freundlich	$q_e = Kc_e^{1/n}$	2	No	No
Redlich-Peterson	$q_e = KMc_e/(1 + Kc_e^\beta)$	3	Yes	No
Toth	$q_e = KMc_e/(1 + Kc_e^\beta)^{1/\beta}$	3	Yes	Yes = M

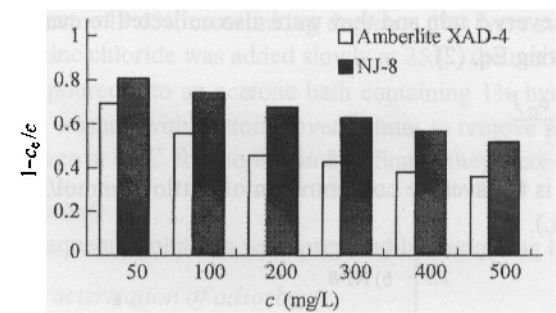


Fig. 2 Yields in elimination at 305 k

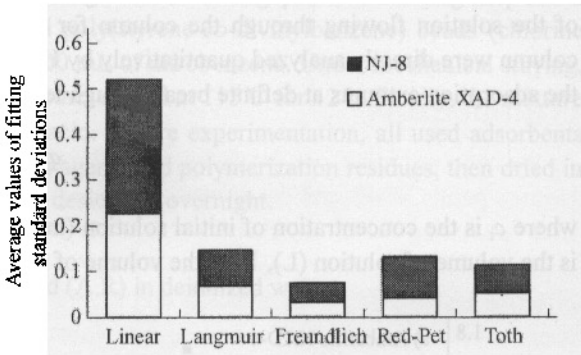


Fig. 3 Averaged standard deviations between the experimental adsorption values and the fitted values by five isotherm models

A nonlinear least-squares analytic method was developed using Origin software. From Fig. 3, our set of experimental data corresponds better to the Freundlich isotherm.

The well-known Freundlich equation has the following logarithmic form:

$$\ln(q_e) = \ln(K_f) + (1/n)\ln(c_e) \tag{3}$$

where K_f and n are characteristic constants.

Applying linear regression to the above form, by taking $\ln(q_e)$ as the dependent variable while $\ln(c_e)$ is the independent variable, by a nonlinear least squares routine the regression equations along with the Freundlich characteristic constants K_f , n and the correlative coefficient R can be found in Table 3.

Table 3. Regression equations of $\ln q_e$ versus $\ln c_e$ for Freundlich isotherms

Adsorbent	Temperature	Regression equation	K_f	n	R
Amberlite XAD-4	291 K	$\ln(q_e) = 0.5208\ln(c_e) + 0.1142$	1.121	1.920	0.997
	305 K	$\ln(q_e) = 0.5472\ln(c_e) - 0.1638$	0.849	1.828	0.999
	319 K	$\ln(q_e) = 0.5517\ln(c_e) - 0.3948$	0.674	1.813	0.998
NJ-8	291 K	$\ln(q_e) = 0.4984\ln(c_e) + 0.5270$	1.694	2.006	0.999
	305 K	$\ln(q_e) = 0.5897\ln(c_e) + 0.4195$	1.521	1.696	0.998
	319 K	$\ln(q_e) = 0.7555\ln(c_e) + 0.1642$	1.178	1.324	0.999

It is quite obvious that the Freundlich equation is in good agreement with the experimental results since the correlative factors R are larger than 0.998 in all cases. So the Freundlich adsorption law is reliable and applicable to the adsorption environment. Based on the Freundlich theory, coefficient K_f is an index of the adsorbing capacity and the exponent n denotes the degrees of deviation from isotherm linearity^[26, 27]. According to K_f in Table 3, the obviously higher adsorbing capacity of NJ-8 toward benzoic acid can be expected. The constant n for NJ-8 is a little larger than that for Amberlite XAD-4, suggesting that NJ-8 provides easier access for benzoic acid into its pores^[28].

It is well known that adsorbing capacity can be affected by several factors, including specific surface area, adsorbent polarity, and pore structures. And the idea that the specific surface area or the mean pore volume may play a major role in an adsorption process has been reported earlier^[29]. But as observed from Table 1, the specific surface area of NJ-8 nearly equals that of Amberlite XAD-4, thus the distinct difference in the adsorption behaviors can by no means be attributed to the specific surface area. However, the micropore area of NJ-8 can be much higher by more than two orders of magnitude than that of Amberlite XAD-4, so the microporous structure of NJ-8 is considered to be one of the predominant factors affecting the studied adsorptive systems and can here be used to explain the superiority of NJ-8. This expression is in good agreement with other reports and can be easily concluded from the capillary condensation theory^[19]. Veverka and Jerbek^[30] have pointed out that the porosity of the hypercrosslinked adsorbents arises mainly from micropores in which the sorption proceeds via a pore filling mechanism rather than by the formation of an adsorbed layer. To apply the concept of surface area evaluation based on the monolayer adsorbing capacity for the hypercrosslinked adsorbents is not quite correct. On the other hand, the polarity matching between polar adsorbate and NJ-8 may partially account for the obvious increase in the adsorbing capacities.

Thermodynamics of the Adsorption

Estimations of the isosteric heat of adsorption, free energy, and entropy were calculated from the data interpolated using the best fitting Freundlich equations. The isosteric heat of adsorption at certain adsorption levels can be easily calculated from the expression derived from the Van't Hoff equation:

$$\ln(c_e) = -\ln(K_0) + \frac{\Delta H}{RT} \quad (4)$$

where ΔH is the isosteric enthalpy of adsorption, K_0 is the parameter, R is the gas constant (kJ/mol-K), and T is the absolute temperature (K).

Equation (4) yields a straight line when representing the logarithm of the inverse of the liquid phase solute concentrations corresponding to a determined value of q_e is plotted versus the inverse of the absolute temperature. The slope of this plot, determined by least-squares analysis of the data obtained at various temperatures, equals the enthalpy over the universal gas constant if ΔH is independent of temperature.

The free energy change of adsorption can be calculated using an expression derived from the Gibbs adsorption isotherm by a procedure shown elsewhere^[31]. Finally, at low solute concentration, the following equation was obtained:

$$\Delta G^1 = -RT \int_0^X q \frac{dX}{X} \quad (5)$$

where ΔG^1 = free energy change of adsorption per unit mass of adsorbent (kJ/mol), and q = mole of solute adsorbed per unit mass of adsorbent (mol/g), and X = mole fraction of adsorbed solute in solution.

The use of the Freundlich isotherm model would lead to a value of the free energy change per mole of solute adsorbed which is independent of q_e in the following form^[31]:

$$\Delta G = -nRT \tag{6}$$

where n represents the Freundlich exponent and it is considered to be related closely to the strength of the adsorption forces between adsorbate and adsorbent^[32].

Entropy change values associated with adsorption can be calculated using previously obtained ΔH and ΔG values by the Gibbs-Helmholtz equation:

$$\Delta S = \frac{\Delta H - \Delta G}{T} \tag{7}$$

The estimated values of thermodynamics properties at different adsorbate loadings are summarized in Table 4.

Table 4. Thermodynamic properties for the adsorption systems

Adsorbent	q_e (mmol/g)	ΔH (kJ/mol)	ΔG (kJ/mol)			ΔS (kJ/mol K)		
			291 K	305 K	319 K	291 K	305 K	319 K
Amberlite XAD-4	0.6	-27.34				-77.99	-74.44	-70.63
	0.8	-23.58	-4.65	-4.64	-4.81	-65.07	-62.11	-58.85
	1.0	-21.45				-57.75	-55.13	-52.17
NJ-8	0.6	-32.67				-95.59	-93.01	-91.40
	0.8	-27.27	-4.85	-4.30	-3.51	-77.03	-75.31	-74.48
	1.0	-23.08				-62.64	-61.57	-61.34

The estimated isosteric heats of adsorption of benzoic acid onto both polymeric adsorbents are low and in the range of 10–40 kJ/mol where physical adsorption is expected to be the dominant mechanism^[33]. Values of enthalpy (always negative) indicate the adsorption process is an exothermic one, as generally expected, ΔH declines with increasing loading, a common situation when dealing with adsorption on heterogeneous surfaces which can be related to the preferential occupation of the superficial locations which are energetically more favorable and dominate, and further to the gradual change in interaction, from that between adsorbate and adsorbent, to that between solute in solution and solute adsorbed on adsorbent^[34].

It is well known that the free energy change value for a physical sorption, which is in the range of -20 to 0 kJ/mol, is less than that for a chemical sorption process, which is in the range of -400 to -80 kJ/mol^[35]. The free energy changes are small, shown in Table 4, further confirming the physical character of the adsorption. And as expected they are negative in all cases because the solute is more concentrated on the surface of the adsorbents than in the bulk solutions. The magnitude of the free energy changes indicates the stronger adsorption force between NJ-8 and benzoic acid for the partially polar groups in its network, in agreement with the results of equilibrium static adsorption.

The negative values of the adsorption entropy are consistent with the restricted mobilities of the adsorbed benzoic acid molecules compared with those in solution. Thus, a more ordered arrangement of solute molecules is formed on the surface of Amberlite XAD-4 compared than that of NJ-8 as reported in other literature^[34, 36]. With increasing superficial coverage, absolute entropy values decrease slightly; the same tendency was reported earlier^[37]. The reason may also be attributed to the superficial heterogeneity of the adsorbents at lower adsorption levels and to the influence of the configuration at higher adsorption levels, which may change with increasing superficial coverage over the adsorbents.

Mini-column Adsorption

The results of mini-column dynamic adsorption of benzoic acid by Amberlite XAD-4 and NJ-8 are shown in Fig. 4.

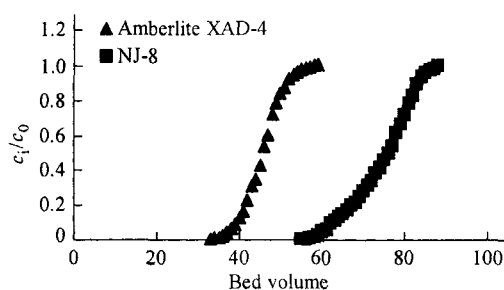


Fig. 4 Breakthrough adsorption curves of benzoic acid by both adsorbents

Breakthrough adsorption capacities for both experiments were calculated by Eq. (2) based on the total amount of benzoic acid removed when the outlet concentration reached 5% or nearly 100% of the feed concentration, and shown in Table 5.

Table 5. Results of benzoic acid adsorption under dynamic conditions with mini-columns

Adsorbents	5% Breakthrough Level		100% Breakthrough Level	
	Capacity (mmol/mL)	Bed volume (BV)	Capacity (mmol/mL)	Bed volume (BV)
Amberlite XAD-4	0.56	36	0.75	59
NJ-8	0.98	58	1.22	89

Both adsorbents show similar trends for the adsorption of benzoic acid. It is worthy of note that NJ-8 adsorbs larger amounts and shows a longer protection time than Amberlite XAD-4. At both breakthrough levels the treated volumes of the solution are about 1.6 times larger than with Amberlite XAD-4. More than 42% increase in the adsorbing capacity of NJ-8 can be calculated in comparison with that of Amberlite XAD-4, in the range of 114.9%–164.8% obtained in the above section.

Acetone is used to desorb benzoic acid from the column. At the flow rate of 2 BV/h, within 1.5 h, nearly 100% regeneration efficiencies for both adsorbents can be achieved, which indicate that the microporous structure of NJ-8 can not ‘trap’ the benzoic acid molecules or prolong the desorption procedure.

CONCLUSIONS

The Freundlich isotherm model can perfectly fit the experimental data in the temperature range of 291–319 K. Due to its hydrophilic groups, hypercrosslinked polymeric adsorbent NJ-8 is water-compatible and has higher adsorbing capacities for benzoic acid, about 14.9%–64.8% greater than Amberlite XAD-4, which are mainly attributed to its microporous structure and can partially be explained by the polarity of its networks. However, the difference has nothing to do with the specific surface area in the range studied.

The enthalpy values of adsorption manifest an exothermic physical adsorption. The free energy changes also confirm that it is a physical adsorption process, and together with the entropy of the adsorption manifest the restricted mobility of the adsorbed solute molecules on the surfaces of both adsorbents. The changes of the adsorption enthalpy and entropy for benzoic acid with various adsorbate loadings both demonstrate the superficial heterogeneity of the adsorbents studied.

The experimental results of mini-column dynamic adsorption toward benzoic acid by Amberlite XAD-4 and NJ-8 further elucidate the higher adsorbing capacity of the latter due to its special character of network and pore. Without doubt, the modified hypercrosslinked polymeric adsorbent NJ-8 has higher capability of removing and recovering many other organic substances having aromatic structure from aqueous media.

REFERENCES

- 1 Faust, S.D. and Aly, O.M., "Adsorption processes for Waste Treatment", Butterworth, Boston, 1987
- 2 Zhu, X.Y., Chen, J.L., Lu, X.X., Zhang, Q.X. and Wang, L.S., Chinese J. of Reactive Polymers, 1998, 7: 22
- 3 Asheh, S.A., Banat, F., Omari, R.A. and Duvnjak, Z., Chemosphere, 2000, 41: 659
- 4 Bandosz, T.J., Jagiello, J., Contescu, C., and Schwarz, J.A., Carbon, 1993, 31: 1193
- 5 Albright, R.L., React. Polym., 1986, 4: 155
- 6 Tai, M.H., Saha, B. and Streat, M., Reactive & Functional Polymers, 1999, 41: 149
- 7 Brosillon, S., Manero, M.H. and Foussard, J.N., Environ. Sci. Technol., 2001, 35: 3571
- 8 David, S.F., Anthony, L.H. and Snie, W.W., J. Colloid Interface Sci., 1979, 69:233
- 9 Xu, Z.Y., Zhang, Q.X., Chen, J.L. and Wang, L.S., Chemosphere, 1997, 35: 2269
- 10 Xu, Z.Y., Zhang, Q.X., Wu, C.L. and Wang, L.S., Chemosphere, 1999, 38: 2003
- 11 Kunin, Pure & Appl. Chem., 1976, 46: 205
- 12 He, B.L. and Huang, W.Q., "Ion exchange and Adsorption resins" (in Chinese), The Science and Education Press, Shanghai, 1992
- 13 Juang, R.S., Shiau, J.Y. and Shao, H.J., Separ. Sci. Tech., 1999, 34: 1819
- 14 Ekberg, B. and Mosbach, K., Trends Botechnol., 1989, 7: 92
- 15 Alexandratos, S.D. and Kaiser, P.T., Ind. Eng. Chem. Res., 1990, 29: 1306
- 16 Davankov, V.A., Rogozhin, S.V. and Tsyurupa, M.P., 1969, USSR Pat., 299165; USA Pat., 3729457
- 17 Davankov, V.A. and Tsyurupa, M.P., React. Polym., 1990, 13: 27
- 18 Tsyurupa, M.P., Maslova, L.A., Andreeva, A.I., Mrachkorskaya, T.A. and Davankov, V.A., React. Polym., 1995, 25: 69
- 19 Azanova, V.V. and Hradil, J., React. Polym., 1999, 41: 163
- 20 Streat, M. and Sweetland, L.A., Trans. IchemE.B., 1998, 76:115
- 21 Catherine, F.B. and Pierre, L.C., J. Environ. Eng., 2001, 127: 889
- 22 Chern, J.M. and Chien, Y.W., Ind. Eng. Chem. Res., 2001, 40: 3775
- 23 Nirmalakhandan, N. and Speece, R.E., Environ. Sci. Technol., 1990, 24: 575
- 24 Zhou, M.L., Martin, G., Taha, S. and Santanna, F., Wat. Res., 1998, 32: 1109
- 25 Liu, M., Zhang, H., Zhang, C., Deng, Y., Liu, W. and Zhan, H., Water Environ. Res., 2001, 73: 322
- 26 Slejko, F.L., "Adsorption Technology: A Step-by-Step Approach to Process Evaluation and Application", Marcel Dekker, New York, 1985
- 27 Carmo, A.M., Hundal, L.S. and Thompson, M.L., Environ. Sci. Technol., 2000, 34: 4363
- 28 Jung, M.W., Ahn, K.H., Lee Y.H., Kin, K.P., Insook, R.P., Rhee, J.S., Jung, T.P. and Paeng, K.J., J. Chromatogr. A., 2001, 917: 87
- 29 Juang, R.S. and Chou, T.C., Separ. Sci. Technol., 1996, 31: 1409
- 30 Veverka, P. and Jerabek, K., Reactive Functional Polymers, 1999, 41: 21
- 31 Bell, J.P. and Tsezos, M., Journal WPCF, 1987, 59: 191
- 32 Powell, T., Brion, G.M., Jagtoyen, M. and Derbyshire, F., Environ. Sci. Technol., 2000, 34: 2779
- 33 Herbes, S.E., Water Res., 1977, 11: 493
- 34 Garcia-delgado, R.A., Cotoruelo, L.M. and Rodriguez, J.J., Separ. Sci. Technol., 1992, 27: 975
- 35 Jaycock, M.J. and Parfitt, G.D., "Chemistry of Interfaces", Ellis Horwood, Chichester, 1981
- 36 Wright, E.H.M. and Powell, A.V., Chem. Soc. Faraday Trans., 1972, 68: 1908
- 37 Bottani, E.J., Llanos, J.L. and Cascarini de torre, L.E., Carbon, 1989, 27: 531