Adsorption Isotherms for Chlorinated Phenols on Activated Carbons

Linda S. Colella and Piero M. Armenante*

Department of Chemical Engineering, Chemistry, and Environmental Science, New Jersey Institute of Technology, University Heights, Newark, New Jersey 07102-1982

David Kafkewitz

Department of Biological Science, Rutgers University, Newark, New Jersey 07102

Stephen J. Allen and Vikram Balasundaram

Department of Chemical Engineering, The Queen's University of Belfast, David Keir Building, Stranmillis Road, Belfast BT9 5AH, U.K.

The adsorption of 12 mono-, di-, and trichlorophenols from aqueous solutions on different activated carbons was studied. Distilled water and a minimal salt medium solution previously used in biotreatment studies with anaerobic organisms were used as solvents. A commercially available wood-based activated carbon (Chemviron carbon) and a lignite-based carbon produced at Queen's University were used as the adsorbents. The Chemviron carbon was used in both granular and powder forms. The adsorption data for each chlorophenol were regressed using the Freundlich equation. The fit was generally satisfactory, especially since the range of chlorophenol concentrations tested in this work extended over 6 orders of magnitude. The exponents of the chlorophenol concentration term in the Freundlich equations were found to be in the relatively narrow range 0.127−0.207. Therefore an attempt was made to regress all the data for all chlorophenols using a single isotherm, and a cumulative Freundlich isotherm was obtained. The Chemviron carbon was found to have a higher adsorbing capacity than the lignite-based carbon. The presence of additional inorganic solutes in the aqueous phase was found to have a negligible influence on adsorption.

Introduction

Because of their widespread use in industry, such as the pulp and paper industry, and their toxicity and recalcitrance, chlorophenolic compounds constitute an important class of environmental pollutants. Chlorophenols have found use as pesticides and biocides, and monochlorophenols can be formed during the breakdown of pesticides and other chlorinated aromatic compounds. Furthermore, some of the less chlorinated chlorophenols (especially monochlorophenols) can be generated during the chlorination of wastewaters (Pritchard et al., 1987). Because of their relatively high solubility, chlorophenols cannot only contaminate wastewaters and groundwaters but also migrate within different aqueous environments (Smith and Novak, 1987).

Therefore, it is not surprising that many investigators have studied the possibility of biodegrading chlorophenols either aerobically and anaerobically (Madsen and Aamand, 1991; Madsen and Licht, 1992; Mohn and Kennedy, 1992). In particular, it appears that anaerobic microorganisms are very effective at partially dechlorinating more chlorinated chlorophenols (Armenante et al., 1992, 1993; Kafkewitz et al., 1992; Madsen and Aamand, 1991; Togna et al., 1995). The resulting degradation products (mono- and dichlorophenols) can be more easily attacked by aerobic microorganisms (Reineke and Knackmuss, 1988; Chaudhry and Chapalamadagu, 1991).

An alternative approach to the removal of chlorophenols from aqueous environments is via adsorption on activated carbons. A number of studies can be found in the literature on this subject (Allen et al., 1995; Nelson and Yang, 1995; Sorial et al., 1993; Shirgaonkar et al., 1992; Kennedy et al., 1992; Peel et al., 1981; Fritz and Schlunder, 1981). Except for some preliminary work by this group (Allen et al., 1995), most of the previous work has been focused on the use of Filtrasorb 400 as the adsorbent. In addition, some of these studies have emphasized the role of variables of importance in the adsorption process (e.g., the role of oxygen during adsorption) rather than determining the adsorption constants for the target compounds. Furthermore, the adsorption isotherms have been determined only for some of the chlorophenols, and for liquid-phase concentrations of the chlorophenols well below the solubility limits.

Because of the possible combined use of biodegradation and adsorption to remove these compounds, it is important to determine the adsorption capability of activated carbons even at high chlorophenol concentrations. In addition, since biodegradation requires the presence of additional substrates in solution, it is important to determine whether the presence of inorganic compounds can have an impact on adsorption.

The focus of this work was to quantify the adsorption of 12 mono-, di-, and trichlorophenols on two different types of activated carbons over a wide range of chlorophenol concentrations, using as solutions water or a minimum salt medium solution previously used in biotreatment studies with anaerobic microorganisms (Armenante et al., 1992,

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* To whom correspondence should be addressed. Fax: (973) 802-1946. E-mail: armenante@admin1.njit.edu.

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1993; Togna et al., 1995). The main objective of the work was to obtain equilibrium isotherms valid for the entire range of chlorophenol concentrations examined and to determine the role of carbon type, particle size, and media type on the equilibrium.

Experimental Section

Activated Carbons. a. Carbon A1. This was a commercially available wood-based activated carbon (WS 45; Chemviron Carbon, Brussels, Belgium). The carbon was in the form of cylindrical pellets approximately 2.5−5 mm in length (average diameter: 3.7 mm) and had a bulk density of 450 g/L (void fraction: 38−42%), a BET surface area of 1100 m^2/g, and a total pore specific volume of 0.75 mL/g. Before use the pellets were repeatedly washed with distilled water and dried overnight at 100 °C.

b. Carbon A2. This carbon was obtained by grinding the washed and dried Carbon A1 in a mortar and sieving the resulting powder. The fraction used in this work passed through the 140 mesh sieve but was retained on the 200 mesh sieve (approximate particle size: 75 μm).

c. Carbon B. This carbon was a lignite-based carbon produced at Queen's University. Lignite obtained from an open cast mine in Crumlin, Co. Antrim, U.K., was heated to 800 °C for 40 min in a negligibly vented atmosphere in order to drive off volatiles and produce a porous carbon structure. After cooling, the carbon was added to an iron nitrate solution to form a slurry (800 mL water, 80 g iron nitrate, 80 g carbon), mixed for 1 h, vacuum-filtered, and dried for 24 h at 105 °C. The resulting particles (1−1.4 mm in size) were further activated at 850 °C by reaction with a measured amount of steam in a constant nitrogen atmosphere (partial steam pressure, 0.926 bar; total pressure, 1.013 bar). This carbon had a specific surface area of 519 m^2/g and a total pore specific volume of 0.34 mL/g. Additional information is provided elsewhere (Allen et al., 1995). The carbon particles were washed with distilled water and dried overnight at 100 °C prior to their use.

Adsorbates. The adsorbates used in this study were 2-chlorophenol (2-CP), 3-chlorophenol (3-CP), 4-chlorophenol (4-CP), 2,3-dichlorophenol (2,3-DCP), 2,4-dichlorophenol (2,4-DCP), 2,5-dichlorophenol (2,5-DCP), 2,6-dichlorophenol (2,6-DCP), 3,4-dichlorophenol (3,4-DCP), 3,5-dichlorophenol (3,5-DCP), 2,3,5-trichlorophenol (2,3,5-TCP), 2,3,6-trichlorophenol (2,3,6-TCP), and 2,4,5-trichlorophenol (2,4,5-TCP). 2-CP, 4-CP, 2,4-DCP, 2,6-DCP, and 2,4,5-TCP (98% to 99% purity) were purchased from Sigma Chemical Co. (St. Louis, MO). 3-CP, 2,3-DCP, 2,5-DCP, and 3,5-DCP, 2,3,5-TCP and 2,3,6-TCP (97% to 99% purity) were purchased from Aldrich Chemical Co. (Milwaukee, WI).

Solutions. Solutions of the adsorbates were prepared using either Milli-RO water or an aqueous minimal salt medium (MSM) as the solvent. The MSM had been previously used as a growth medium during the anaerobic dechlorination of aromatic phenolic compounds (Armenante et al., 1992, 1993; Togna et al., 1995). Its composition was as follows (in g/L): KH_2PO_4, 0.45; K_2HPO_4, 0.225; $MgSO_4 \cdot 7H_2O$, 0.09; $FeSO_4 \cdot 7H_2O$, 0.002; $(NH_4)_2SO_4$, 0.20; $NaHCO_3$, 2.5; sodium formate, 2.0; sodium acetate, 2.5. In addition, the MSM contained 4.08 g/L of a commercially available nonfermentable buffering agent (Bicine; Sigma Chemical Co., St. Louis, MO). The total molar concentration in the MSM was 0.121 mmol/L.

Adsorption Procedure. High-concentration (250−10000 mg/L) stock solutions were prepared for each adsorbate and used to prepare the adsorbing solutions by dilution with Milli-RO water or MSM.

Adsorption experiments were conducted by adding about 0.1 g of one of the carbons (the exact mass, accurate to ±1 mg, was noted in each case) to 160 mL serum bottles filled with the appropriately diluted solution up to 130 mL. The concentrations of the adsorbates in the solutions were typically in the range 100−4000 mg/L. A nominal mass of 0.05 g of carbon was used in the experiments with 2,6-DCP, 2,3,5-TCP, and 2,3,6-TCP owing to the low solubility of these compounds. For each compound, 3−14 bottles (typically 10) were prepared, each one having a different initial concentration. Controls consisted of sample bottles containing the same concentration of adsorbate, but without carbon pellets. All bottles were crimp-sealed with butyl rubber stoppers, immediately autoclaved to prevent microbial degradation of the compounds, and incubated at 25 °C.

In all the experiments with Carbon A1 except that with 4-CP, the bottles were initially allowed to stand for approximately 60 days to allow sufficient time to reach equilibrium. Samples (2 mL) were then taken and analyzed. Additional samples were taken after 7 more days to ensure that equilibrium had been attained. All other bottles were sampled at 3 to 4 day intervals over a 30-day period. The sample volumes ranged from 0.1 to 0.5 mL, depending on the dilution required for analysis.

Although chlorophenols are not very volatile under the conditions of these experiments, the headspace of the bottles was occasionally analyzed by gas chromatography to verify that the disappearance of the compound in the liquid was due to adsorption and not volatilization.

Analytical Methods

All liquid samples were analyzed by HPLC (Waters, Inc.) provided with a Waters 715 Ultrawisp Sample Processor, a Waters 600E System Controller, a Waters 484 Tunable Absorbance Detector set at 280 nm, and an Alltech Econosphere C8 50 Column (length = 150 mm, i.d. = 4.6 mm). The mobile phase used was a 50:50 mixture of two solutions, the first containing 1 vol % acetic acid in methanol, and the second 1 vol % acetic acid in Milli-Q water. The flow rate was 1 mL/min, and the mode of operation was isocratic. The samples were discarded once sampling was completed.

Headspace samples were analyzed using a Shimadzu gas chromatograph provided with a flame ionization detector.

Interpretation of Experimental Data

No appreciable amount of the chlorophenol under examination was ever detected in the headspace. Because of the small sample volumes, the effect of multiple sampling of the liquid phase was found to have a negligible impact on the chlorophenol mass balance in the bottles. The final chlorophenol concentration in the control bottles was typically within ±5% of the initial concentration, although higher deviations were occasionally noticed.

Although the chlorophenol concentration in the bottles changed with time as adsorption proceeded, the majority of chlorophenol uptake (typically in excess of 80% in all cases) always took place prior to the first sample (7 days). However, some changes in the liquid-phase concentration were detected up to 60 days when Carbon A1 pellets were used. In all other cases, minimal or no change was detected among the samples collected after 2 weeks.

The reproducibility of the experimental results was calculated using couples of bottles that had similar final concentrations of the same chlorophenol in solution. The amount of chlorophenol adsorbed in each bottle was calculated and compared to the other. It was found that the average deviation was 7.5%.

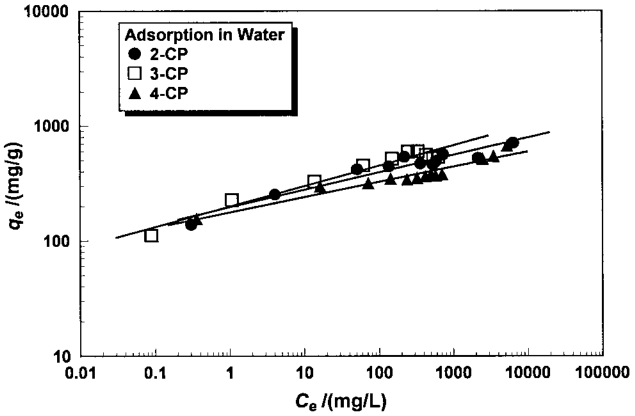

Figure 1. Adsorption data and isotherms for monochlorophenols (2-CP, 3-CP, and 4-CP) on Carbon A2 in water. Temperature = 25 °C.

The experimental equilibrium data, expressed as q_e (amount of chlorophenol adsorbed per mass of carbon, in mg/g or mmol/g, as noted) vs C_e (final chlorophenol concentration in solution, in mg/L or mmol/L, as noted) were interpreted using the Freundlich equation:

$$q_e = k \cdot C_e^{1/n} \qquad (1)$$

The proportionality constant k (having the units of (mg/g)/[(mg/L)$^{1/n}$] or (mmol/g)/[(mmol/L)$^{1/n}$], depending on the units of q_e and C_e, as noted) and the exponent $1/n$ (nondimensional) were obtained by linearly regressing each set of experimental data using the following equation:

$$\log(q_e) = \log(k) + {}^1/_n \log(C_e) \qquad (2)$$

A standard regression analysis was performed on each set of data to calculate the correlation coefficient for each regression, as well as the standard error of the estimate, and the values of the standard errors for the coefficients k and $1/n$ (Lapin, 1975).

An attempt was also made to interpret the data using the Langmuir equation. However, the fit was typically found to be very poor (results not shown).

Results and Discussion

The majority of the experiments performed in this study were obtained using Carbon A2 and water. The adsorption isotherms for 2-CP, 3-CP, and 4-CP in water on Carbon A2 are given in Figure 1. The corresponding values of the Freundlich parameters for each chlorophenol were obtained from eq 2 and are reported in Table 1. The values of the correlation coefficients (Table 1) indicate that the Freundlich isotherm adequately correlates the experimental data. The isotherms for all dichlorophenols are reported in Figure 2 (2,3-DCP, 2,4-DCP and 2,5-DCP) and Figure 3 (2,6-DCP, 3,4-DCP, and 3,5-DCP). Finally, the isotherms for the trichlorophenols (2,3,5-TCP, 2,3,6-TCP, and 2,4,5-TCP) are shown in Figure 4. The values for the Freundlich parameters are also reported in Table 1. The correlation coefficients of the isotherms for di- and trichlorophenols (Table 1) were comparable to those for monochlorophenols.

The average percent standard error of the estimate (i.e., the average percent deviation of the experimental data for each adsorbate from the corresponding Freundlich regression curve) was found to be 11.05%, i.e., of the same order of magnitude of the deviation in the reproducibility of the experiments (7.5%). However, the standard error was relatively small for some chlorophenols (e.g., 3.0% for 2,4-DCP) and large for others (e.g., 17.5% for 2,5-DCP).

Table 1. Freundlich Parameters for the Adsorption of Chlorophenols on Carbon A2 from Water (Temperature = 25 °C)

compound	k/(mg/g)/[(mg/L)$^{1/n}$]	$1/n$ (−)	correlation coefficient
2-CP	195.45 ± 16.02	0.152 ± 0.014	0.963
3-CP	198.58 ± 13.16	0.177 ± 0.014	0.977
4-CP	176.64 ± 12.38	0.133 ± 0.012	0.960
2,3-DCP	398.75 ± 11.34	0.130 ± 0.007	0.992
2,4-DCP	502.21 ± 12.58	0.127 ± 0.005	0.995
2,5-DCP	218.72 ± 51.10	0.180 ± 0.041	0.874
2,6-DCP	176.85 ± 3.63	0.207 ± 0.007	0.996
3,4-DCP	276.49 ± 23.17	0.124 ± 0.017	0.946
3,5-DCP	238.98 ± 7.43	0.118 ± 0.009	0.969
2,3,5-TCP	314.37 ± 20.15	0.200 ± 0.028	0.946
2,3,6-TCP	259.92 ± 9.90	0.154 ± 0.014	0.974
2,4,5-TCP	244.95 ± 14.22	0.163 ± 0.017	0.952

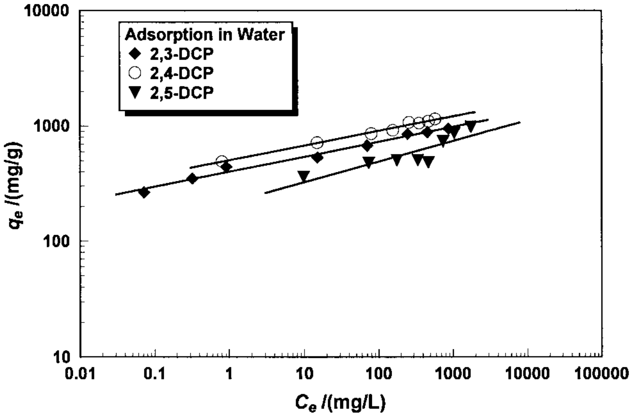

Figure 2. Adsorption data and isotherms for three dichlorophenols (2,3-DCP, 2,4-DCP and 2,5-DCP) on Carbon A2 in water. Temperature = 25 °C.

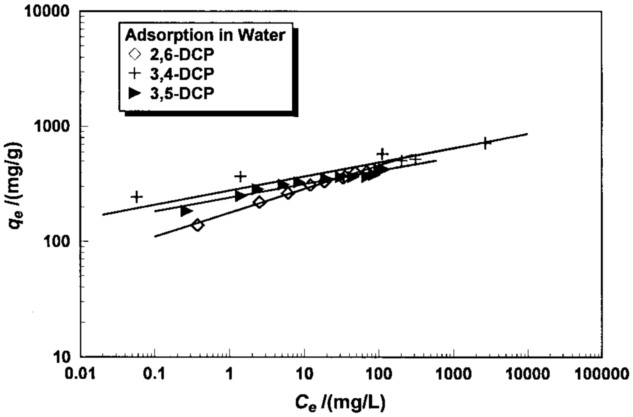

Figure 3. Adsorption data and isotherms for three dichlorophenols (2,6-DCP, 3,4-DCP, and 3,5-DCP) on Carbon A2 in water. Temperature = 25 °C.

A comparison of Figures 1−4 shows that monochlorophenols are more weakly absorbed on Carbon A2 than more highly chlorinated phenols. This is also apparent from a comparison of the k values in Table 1. Generally speaking, no clear-cut preference in the order of adsorption of di- and trichlorophenol is evident from the data. However, when the data are grouped into separate mono-, di-, and trichlorophenol groups a trend can be seen. Table 2 shows that the combined isotherm for all monochlorophenols has a value of k appreciably lower than those for di- or trichlorophenols. By comparison, the difference between the k values of the isotherms for di- and trichlorophenols is

Table 2. Freundlich Parameters for the Adsorption of Groups of Chlorophenols on Carbon A2 from Water (Temperature = 25 °C)

q_e in mg/g; C_e in mg/L

chlorophenol group	k/(mg/g)/[(mg/L)$^{1/n}$]	$1/n$ (−)	correlation coefficient
monochlorophenols	194.97 ± 12.65	0.143 ± 0.011	0.910
dichlorophenols	274.79 ± 18.51	0.151 ± 0.015	0.807
trichlorophenols	272.24 ± 10.08	0.156 ± 0.012	0.925
all chlorophenols	262.45 ± 10.72	0.131 ± 0.009	0.802

q_e in mmol/g; C_e in mmol/L

chlorophenol group	k/(mmol/g)/[(mmol/L)$^{1/n}$]	$1/n$ (−)	correlation coefficient
all chlorophenols	3.294 ± 0.092	0.149 ± 0.008	0.872

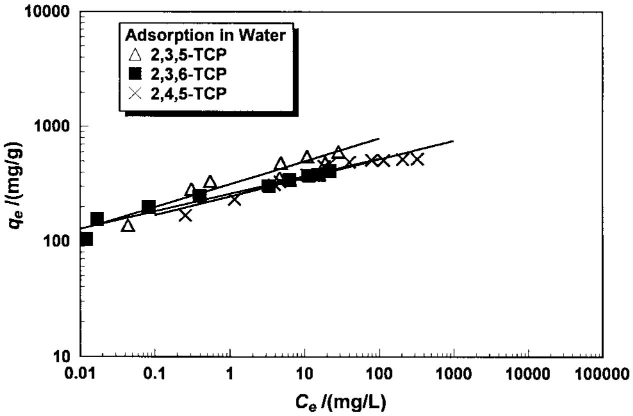

Figure 4. Adsorption data and isotherms for trichlorophenols (2,3,5-TCP, 2,3,6-TCP, and 2,4,5-TCP) on Carbon A2 in water. Temperature = 25 °C.

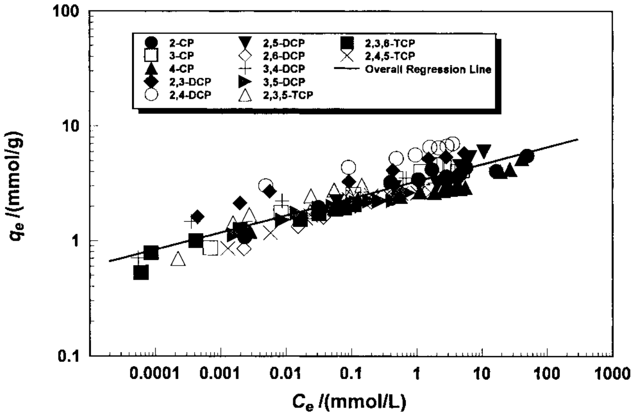

Figure 5. Combined data for all chlorophenols and overall adsorption isotherm. Temperature = 25 °C.

minimal. The values of the exponents, $1/n$, for the mono-, di-, and trichlorophenols are all relatively similar to each other (range: 0.143−0.156; Table 2) and increasingly higher. The similarities among the $1/n$ values and the small differences among the k values suggest that it should be possible to produce a combined isotherm for all chlorophenols, capturing the essence of the adsorption equilibrium. A regression of all the combined data was obtained. The slope and intercept for this overall isotherm are also given in Table 2. To improve this regression, the same data were further regressed using molar units for the adsorbates (i.e., expressing q_e and C_e in terms of mmol of chlorophenol/g of carbon and mmol of chlorophenol/L, respectively). The slope and intercept for this overall isotherm are also given in Table 2. Figure 5 shows a plot of all combined data. The scatter of the data (correlation coefficient = 0.872) seems acceptable considering that data for a large number of different chlorophenols were combined together in a single isotherm and that the data spanned over a 6 orders of magnitude range of concentrations. This isotherm could be used in the preliminary estimation of chlorophenol adsorption equilibria.

The results of this work can be partially compared, as far as Carbon A2 is concerned, with those of Shirgaonkar et al. (1992), who studied a more limited number of chlorophenols using Filtrasorb 400, a commercially available coal-based activated carbon, as the adsorbing material. The comparison is, in general, quite favorable, especially for monochlorophenols. Dichlorophenol isotherms are also comparable. However, their slopes are typically slightly lower than those found here. Only a limited comparison can be made with their results for trichlorophenols since they only studied one.

Sorial et al. (1993) studied the adsorption of 4-CP on different types of carbons, including three bituminous coal-based carbons, a lignite coal-based carbon, and a wood-based carbon. The isotherm that they obtained with the wood-based carbon (similar to Carbon A in this study) has a much smaller k value and a much larger $1/n$ value than those found here. However, their results with bituminous coal-based carbons are similar to those in the present study.

Recently, Nelson and Yang (1995) have produced adsorption isotherms for eight chlorophenols (including five that were also studied in the present work) on Filtrasorb 400 activated carbon. They divided their results into two groups, depending on the concentration range in the liquid phase: low concentration (approximately below 10−20 μmol/L) and high concentration (approximately 20−700 μmol/L) data. These concentrations correspond roughly (depending on the chlorophenol) to the ranges 0.1−3 mg/L and 3−200 mg/L, respectively. This range is much more limited than that considered in this work (0.05−6000 mg/L). Nevertheless, the agreement between their Freundlich adsorption constants and those found here is substantial, especially considering that they used a different carbon material and that their study was conducted at 30 °C. For example, the values of the Freundlich constants k (converted to the units used here, i.e., (mg/g)/[mg/L]$^{1/n}$) and $1/n$ that they found for 2-CP were, respectively, 189.4 and 0.193 (low concentration range) and 205.4 and 0.143 (high concentration range). These values can be compared with 195.45 and 0.152, respectively, found in this work.

Effect of Particle Size. The effect of particle size was tested using two sizes of carbon pellets, one much larger than the other (3700 μm for Carbon A1 vs 75 μm for Carbon A2). The resulting isotherms for three different chlorophenols are given in Figure 6. In the case of 4-CP, although the regression lines intersect each other (a likely artifact of the regression calculations), no appreciable difference between the experimental points is evident (Figure 6a). In fact, a closer inspection of this figure shows that the experimental data nearly overlap in the concentration

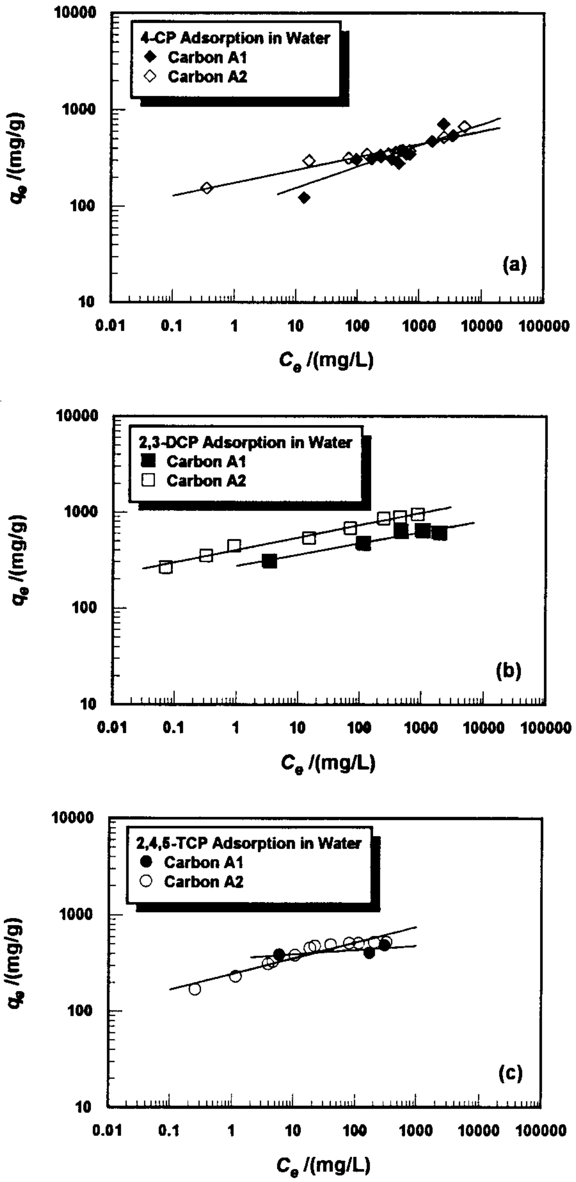

Figure 6. Effect of particle size on the adsorption of 4-CP (a), 2,3-DCP (b), and 2,4,5-TCP (c) in water using Carbon A1 (3700 μm) and Carbon A2 (75 μm). Temperature = 25 °C. The first experimental point for Carbon A1 in panel a was not included in the calculation of the corresponding regression line.

range 100−1000 mg/L. No meaningful conclusions can be drawn for the difference in adsorption capability below 100 mg/L since only one point for Carbon A1 falls in this region. The data points are nearly superimposable also for C_e above 1000 mg/L.

The data for 2,3-DCP (Figure 6b) indicate that the larger particles consistently have a lower adsorption capacity over the range of solute concentrations studied, although this difference is not too significant. In the case of 2,4,5-TCP (Figure 6c), the data indicate a negligible effect due to particle size. In this figure the experimental data points overlap, even though the regression lines may indicate a slightly different trend.

In conclusion, particle size does not appear to play a significant role on chlorophenol adsorption, although larger particles are associated with a slightly diminished adsorption capacity.

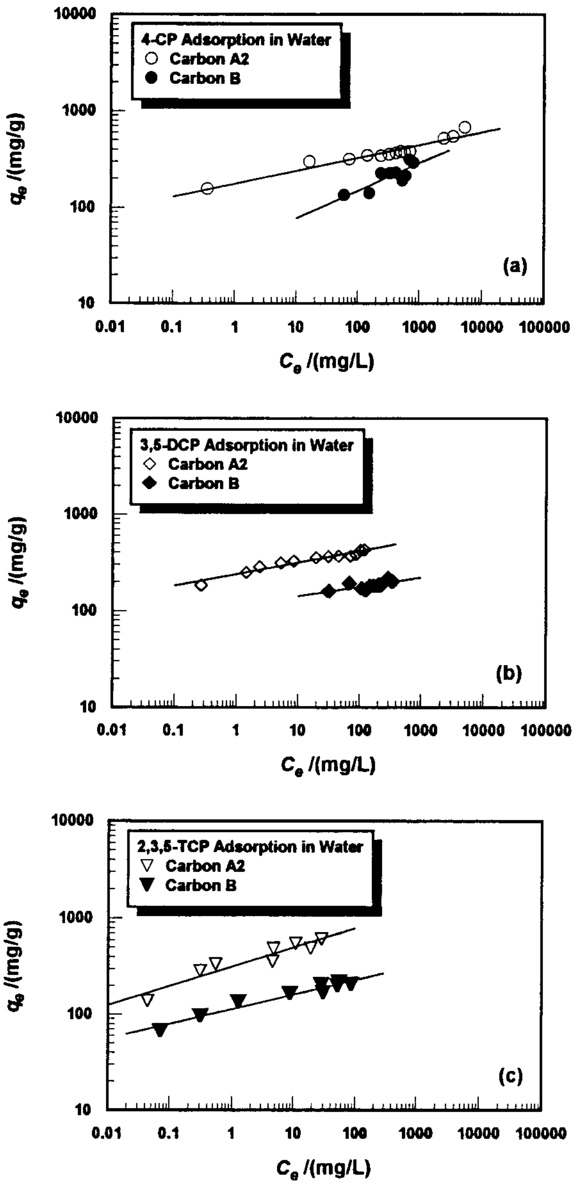

Figure 7. Effect of carbon type on the adsorption of 4-CP (a), 3,5-DCP (b), and 2,3,5-TCP (c) in water using Carbon A2 and Carbon B. Temperature = 25 °C.

Table 3. Freundlich Parameters for the Adsorption of Selected Chlorophenols on Carbon B from Water (Temperature = 25 °C)

compound	k/(mg/g)/[(mg/L)$^{1/n}$]	$1/n$ (−)	correlation coefficient
4-CP	40.03 ± 16.81	0.285 ± 0.069	0.840
3,5-DCP	112.69 ± 17.91	0.097 ± 0.031	0.718
2,3,5-TCP	112.58 ± 4.69	0.153 ± 0.013	0.974

Effect of Carbon Type. The adsorption of chlorophenols from water on Carbon A2, a wood-based carbon, was compared with that on Carbon B, a lignite-based carbon. The results for 4-CP, shown in Figure 7a, indicate that Carbon B has an appreciably lower adsorption capacity. This is consistent with the lower specific surface area and total pore specific volume of Carbon B with respect to Carbon A. A regression of the data produced a slope of 0.285 for Carbon B and 0.133 for Carbon A2. The first of these two slopes is higher than the slopes of the other isotherms reported in Table 1. However, a larger slope (0.548) for the isotherm of sodium benzoate adsorbing on the same type of carbon (Carbon B) used in this work was also reported by Allen et al. (1995).

Table 4. Freundlich Parameters for the Adsorption of 4-Chlorophenol from Water and MSM (Temperature = 25 °C)

carbon type	solvent	k/(mg/g)/[(mg/L)$^{1/n}$]	$1/n$ (−)	correlation coefficient
Carbon A1	water	71.96 ± 15.26	0.259 ± 0.033	0.924
	MSM	61.55 ± 11.64	0.306 ± 0.032	0.950
Carbon A2	water	176.64 ± 12.38	0.133 ± 0.012	0.960
	MSM	107.87 ± 9.34	0.160 ± 0.014	0.969
Carbon B	water	40.03 ± 16.81	0.285 ± 0.069	0.840
	MSM	1.50 ± 2.65	0.748 ± 0.222	0.786

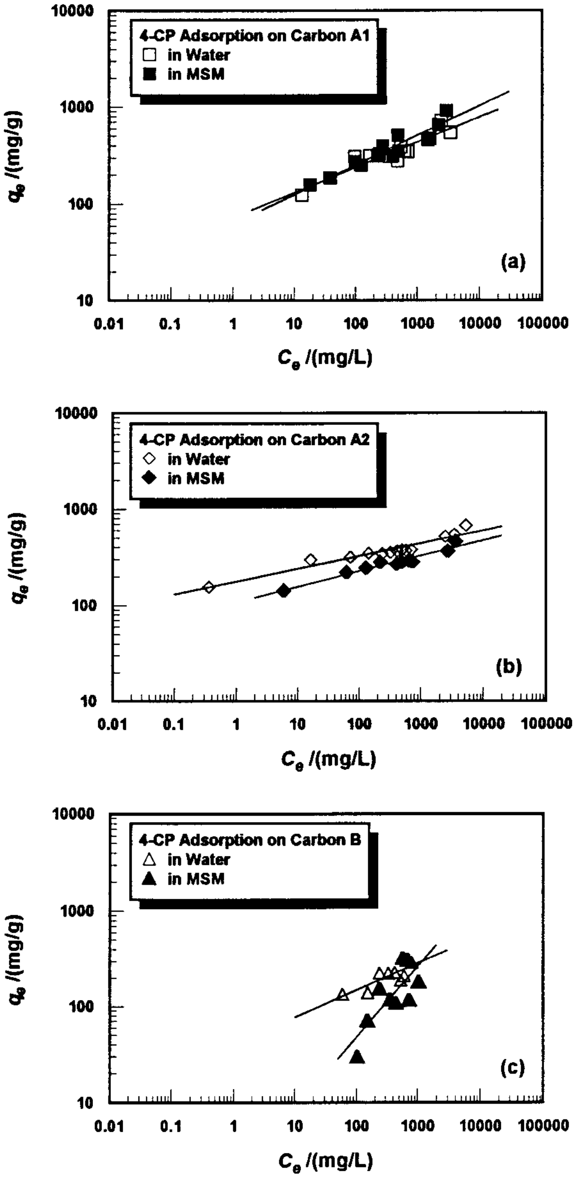

Figure 8. Effect of solution composition on the adsorption of 4-CP on Carbon A1 (a), Carbon A2 (b), and Carbon B (c) using water and MSM (cumulative concentration of electrolytes and buffer agent = 0.121 mmol/L). Temperature = 25 °C.

When more highly chlorinated molecules were used, a significant reduction in the adsorption capacity for Carbon B was also found, as shown in parts b and c of Figures 7 for 3,5-DCP and 2,3,5-TCP, respectively. This reduction is of the order of $^{1}/_{3}$ to $^{1}/_{2}$, as indicated by the k values reported in Table 3 for Carbon B vs those for Carbon A2 given in Table 1. The slopes of the regression lines were found to be lower but similar to those for the same compound adsorbed on Carbon A2.

Little information is available in the literature on the adsorption of chlorophenols on lignite-based carbons. Sorial et al. (1993) obtained an isotherm for 4-CP on this type of carbon. Their values for k and $1/n$ are, respectively, appreciably higher and lower than those found here. This is not surprising since the adsorption parameters for this type of coal exhibit a significant variability depending on their origin and the compounds used in their activation (Allen et al., 1995). Furthermore, the isotherm parameters are significantly different that those found with other types of carbons, even for the same adsorbate.

Effect of Solution Composition. The experiments to determine the effect of the solution composition were all carried out with 4-CP as the adsorbate. The presence of an anaerobic medium such as MSM had a negligible effect on the adsorption capacity of Carbon A1, as shown in Figure 8a. The resulting regression lines were very similar, as indicated by the regression parameters reported in Table 4.

Figure 8b shows that MSM slightly decreased the adsorption capacity for Carbon A2. The slope of the regression line for the adsorption from MSM was found to be slightly higher than that from water, indicating that the effect of the medium decreased as the solute concentration reached the upper limits reached in this study. A comparison between parts a and b of Figures 8 shows that the slopes of the isotherms obtained with Carbon A1 are higher than those obtained with Carbon A2 even when MSM was used. This is similar to the difference in slope observed with the same carbons in water.

Finally, Figure 8c shows that the presence of the MSM resulted in reduced adsorption at lower solute concentration. As in the case of water the slope of the isotherm is higher for Carbon B than for Carbon A. However, the scatter of the data in this figure is significant enough to prevent any further analysis.

Conclusions

In this work the adsorption characteristics of 12 chlorophenols on different carbons and from different media were determined. Although the range of chlorophenol concentrations explored spanned more than 6 orders of magnitude, the adsorption data for each type of chlorophenol on powdered Chemviron Carbon could be adequately regressed using the Freundlich equation. In addition, an overall isotherm equation was determined that regressed all adsorption data for all chlorophenols. This equation can be used for preliminary adsorption calculations. Grinding the carbon to produce a smaller particle size had little impact on equilibrium adsorption. Using a lignite-based carbon as adsorbent resulted in a lower adsorption capacity. The use of an adsorbing solution different from water was found to have a negligible effect on adsorption.

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