

Sorption of Chromium Ions from Aqueous Solution onto Chemically Activated Carbons Developed from Maize Cobs

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(Received July 14, 2008; Accepted September 30, 2008)

Abstract

Chemically activated carbons were prepared from maize cobs, using phosphoric acid of variable concentration. The textural parameters of the activated carbons were determined from the nitrogen adsorption isotherms measured at 77 K. The chemistry of the carbon surface was determined by measuring the surface pH, the pH_{PZC} and the concentration of the carbon - oxygen groups of the acid type on the carbon surface. Kinetics of Cr(VI) sorption/reduction was investigated at 303 K. Two processes were investigated in terms of kinetics and equilibrium namely; Cr(VI) removal and chromium sorption were studied at various initial pH (1-7). Removal of Cr(VI) shows a maximum at pH 2.5. At $pH < 2.5$, sorption decreases because of the proton competition with evolved Cr(III) for ion exchange sites. The decrease of sorption at $pH > 2.5$ is due to proton insufficiency and to the decrease of the extent of Cr(VI) reduction. The chemistry of the surface of activated carbon is an important factor in determining its adsorption capacity from aqueous solutions particularly when the sorption process involves ion exchange.

Keywords: Textural parameter, Kinetics, Equilibrium, Adsorption, Chromium, Active carbon, Maize cobs

1. Introduction

The removal of toxic metal ions from aqueous solutions received a great deal of attention in the last years. Recently, Stringent statutory regulations have been introduced to reduce the discharge of toxic metals to low levels. The main sources of heavy metal pollution include: mining, petroleum, textile, milling and surface finishing industries which discharge a variety of toxic metals into the environment [1]. Treatments such as chemical precipitation membrane filtration, ion exchange, carbon sorption and coprecipitation adsorption have been suggested for the removal of heavy metals from wastewater [2]. Among these methods, carbon sorption is the most reactive because of its simplicity and economical feasibility [3,4].

Hexavalent chromium is a toxic metal present in industrial waste water from various sources such as electroplating, leather tanning and mining industries, cement, steel and fertilizer manufacture, textile dyeing, wood preservative manufacture and photographic industries [5]. Such hexavalent chromium is primarily present in the form of CrO_4^{2-} ions. It leads to liver damage, pulmonary congestion and Edema, and causes skin irritation in ulcer formation. The tolerance limit of Cr(VI) for discharge into inland surface water is 0.1 mg/l and in potable water is 0.05 mg/l [6].

The removal of Cr(VI) ions by activated carbon adsorption provides an effective and good alternative method [7].

Several recent publications have been devoted to prepare activated carbons from different inexpensive and abundantly available precursors such as leaf mould, coconut shells, saw dust, rice husk, used tyre carbon, cane bagasse, olive stones, cotton stalks and others.

Maize cobs are a cheap and abundant agricultural waste of no economic value. However, maize cobs-activated carbons have shown to be a highly porous and rich in microporosity and exhibiting high sorption capacity for methylene blue and Pb^{2+} [8]. Also chemically-activated carbons with an essential microporous structure could be obtained using zinc chloride or phosphoric acid as activating agents [9].

Adsorption of Cr(VI) on activated carbons and other sorbents has been the subject of several investigations [10,11,12,13]. However, the reported results are variable, particularly, in terms of optimum pH of chromium removal. Reduction of Cr(VI) to Cr(III) was observed with different sorbents [14,15]. Taking this in mind, more studies are still required towards improving knowledge already available.

In the present investigation, two processes were studied: Cr(VI) removal and chromium sorption. Cr(VI) removal from aqueous solution occurs via reduction to Cr(III) and adsorption of Cr(VI) on the sorbent surface. The process is followed by analyzing Cr(VI) concentration in the aqueous solution. However, chromium sorption refers to the uptake of total chromium, Cr(VI) and evolved Cr(III) from the aqueous solution by the sorbent and the process is followed

by analyzing total chromium in the aqueous solution. Both processes were investigated using initial Cr(VI) concentration, 180 mg/l, in the initial pH range 1.0-7.0. Different kinetic models were examined. The textural properties were determined from the nitrogen adsorption at 77 K and the chemistry of the surface of the investigated carbon was also investigated.

2. Experimental

2.1. Sorbents

Dried ground maize cobs were first thoroughly washed with water and then dried at 383 K, after cooling to room temperature; they were soaked for 72 h in phosphoric acid solution of concentration 20, 40 and 60 wt. % with occasional shaking. The treated cobs were then filtered and dried to constant weight at 343 K. The dried treated samples were then carbonized in absence of air at 723 K. The carbonized products were then washed several times with distilled water until the pH of the resulting wash solution was c.a 6.0. Finally the carbonized products were crushed and then sieved with the particles within the range 100~200 μm being used in the sorption measurements. In the designation of the carbons employed, C denotes maize cobs and P indicates treatment with phosphoric acid and the Arabic number following the letter P giving the wt% of phosphoric acid employed. Thus, for example, CP40 stands for an activated carbon prepared by activation with 40 wt. % phosphoric acid at 723 K. All the chemicals used were of analytical grade.

2.2. Characterization of the sorbents

The textural properties (Specific Surface area and porosity) were determined from the adsorption of nitrogen at 77 K using conventional volumetric apparatus; the carbon sample was degassed at 473K for 8 h under a reduced pressure of 10^{-5} Torr, prior to nitrogen adsorption. The chemistry of the carbon surface was investigated by measuring the surface pH, the pH of the carbon at the point of zero charge pH_{PZC} and the relative concentration of the surface functional groups of acidic type in the carbon [16]. The surface pH was measured following the ASTM method [17] (1.0 g of the carbon sample was placed in 50 ml stoppered glass bottle containing 20 ml CO_2 - free distilled water. The bottles with their contents were shaken for 4 h and kept for 24 h at room temperature. The pH of the supernatant liquid was determined). Through the use of the mass-titration method [18], pH_{PZC} were determined by placing various amounts of carbons in 50 ml of 0.1 M KNO_3 solution in 100 ml bottles. The sealed bottles were then placed in a thermostat shaker overnight after which the

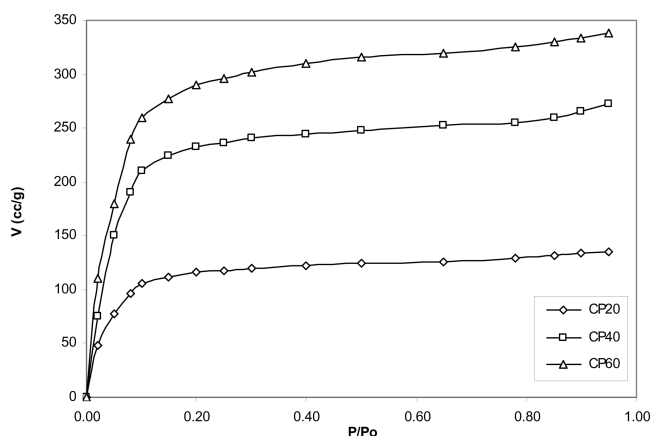


Fig. 1. Adsorption isotherms nitrogen at -196°C onto CP20, CP40 and CP60.

equilibrium pH value of the mixture was measured. The limiting pH was taken as the value of pH_{PZC} .

The nitrogen adsorption isotherms (Fig. 1) are all type I according to Sing classification [20]. The specific surface areas S_{BET} (m^2/g) were determined by applying the conventional BET equation [21] and the total pore volume V_{T} (ml/g) is read from the nitrogen uptake at $P/P_0=0.95$. The micropore volume V_{m} (ml/g) is determined from the nitrogen uptake at $P/P_0=0.1$ and the mean pore radius r_{m} (nm) is calculated from the relationship

$$r_{\text{m}} = \frac{2V_{\text{T}} \cdot 10^3}{S_{\text{BET}}}$$

These textural parameters of the investigated carbons are listed in Table 1. Table 1 indicates that all the investigated carbons contain a large fraction of micropores and that the total pore volume and surface area increase with the increase of the concentration of phosphoric acid used. More details on the function of phosphoric acid and the activation process are reported elsewhere [22].

2.3. Adsorption from solution

A stock solution of Cr(VI), 1000 mg/l, was prepared in distilled water using $\text{K}_2\text{Cr}_2\text{O}_7$ and all the working solutions were prepared by dilution in distilled water. Kinetic and batch experiments were undertaken by mixing 0.1 g carbon with 100 ml of Cr(VI) solution (180 mg/l) at required initial pH (1.0-7.0) at 303 K, in a shaking water bath (200 rpm). The pH was adjusted by adding few drops of 0.1 M H_2SO_4 or 0.1 M NaOH prior to the addition of the sorbent.

Cr(VI) in solution was analyzed with Perkin - Elmer UV-Vis spectrophotometer model 550s using 1,5 diphenyl-carbazide in acid medium [19]. Total chromium was determined using Perkin - Elmer atomic 2380 absorption spectrophotometer. The difference in concentration between the total chromium and Cr(VI) gives Cr(III) concentration.

Table 1. Textural Properties of the Sorbents Investigated

Sorbent	S_{BET} (m ² /g)	V_{T} (ml/g)	V_{m} (ml/g)	r_{m} (nm)	$V_{\text{m}}/V_{\text{T}}$
CP20	410.0	0.209	0.164	1.02	0.785
CP40	847.0	0.422	0.325	1.00	0.770
CP60	1016.0	0.524	0.403	1.03	0.769

Table 2. pH_{PZC} , Surface pH of the Carbons Investigated and the Amount of Surface Acid Groups (meq/g)

Sorbent	pH_{PZC}	Surface pH	Surface acid functionality				
			Carboxyl	lactonic	phenolic	carbonyl	Total
CP20	2.9	4.2	0.54	0.37	0.48	0.30	1.69
CP40	2.6	3.7	1.45	0.52	1.28	0.46	3.71
CP60	2.2	4.0	2.35	0.63	2.05	0.64	5.71

Experiments and analyses were carried out three times with the difference, in all cases not exceeding 2.5%.

For the kinetic experiments at different periods of time, the pH of the reaction solution was measured and aliquot of supernatant was withdrawn for the analysis of Cr(VI) and total chromium. For the batch experiments, after the equilibrium time was reached, the final pH was recorded and aliquot of supernatant was withdrawn and analyzed for Cr(VI) and total chromium.

3. Results and Discussion

3.1. The chemistry of the carbon surface

The chemistry of the surface of an activated carbon is equally important to its textural parameters in determining its adsorption capacity. However, the chemistry of the carbon surface is more important than the textural parameters in case of adsorption from solution. Moreover, the role of the chemistry of the surface dominates the sorption from solution when the process involves cation exchange or charged species as in the case of metal ion sorption.

The chemistry of the carbon surface is mainly due to the existence at the surface of carbon-oxygen groups of acidic or basic type. However, for chemically - activated carbons, the density of the surface acidic groups is too high to mask the function of surface basic groups. The acidic carbon-oxygen groups include carboxylic, lactonic, phenolic and carbonyl groups. They are quantitatively determined by neutralization with basic groups of varying strength. Thus NaHCO_3 neutralizes carboxylic groups whereas Na_2CO_3 determine both carboxylic and lactonic groups. NaOH as a strong base determine carboxylic, lactonic and phenolic groups. NaOC_2H_5 neutralizes carboxylic, lactonic, and phenolic groups, in addition to reaction with carbonyl group [23].

The surface pH is conventionally used as an indicator of the surface groups and pH_{PZC} is another indicator of the surface functional groups on carbon sorbents. Table 2 lists the amount of surface acid groups (meq/g) together with the

surface pH and pH_{PZC} of the sorbents investigated. Table 2 reveals that: (i) the surface acidity as indicated by the decrease of both surface pH and pH_{PZC} increased with the increase of the concentration of phosphoric acid used in carbon activation (ii) For all sorbents, carboxylic groups are more dominating, followed by phenolic groups and then come the lactonic groups. The concentration of the carbonyl groups are slightly lower than the concentration of lactones, this is true for all the sorbents. However, the reaction of carbonyl groups with NaOC_2H_5 is not a neutralization reaction since it does not involve exchange either by H^+ or Na^+ ions.

3.2. Adsorption from solution

3.2.1. Equilibrium experiments

Many investigations have been devoted to studying Cr (VI) sorption and a general agreement has been reported that Cr(VI) sorption depends on the initial pH of the sorption solution but, no agreement has been reached on the optimum pH of Cr(VI) sorption. This may be ascribed to variations in sorption conditions such as sorbent type, chemistry of the

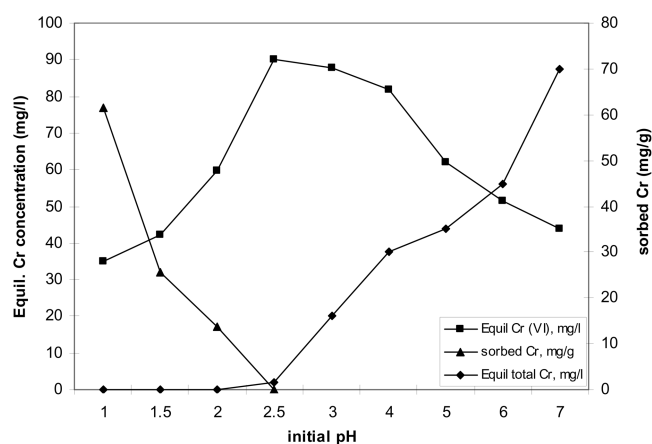


Fig. 2. Equilibrium Cr concentrations, equilibrium total Cr and sorbed Cr at different initial pH values at 30°C. (initial Cr (VI) concentration 180 mg/l).

Table 3. Initial pH, Final pH and Amount of Chromium Sorbed (mg/g) Onto CP60

Initial pH	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0
Final pH	1.1	1.7	2.3	4.3	5.0	6.1	6.5	6.9	7.6
Cr sorbed	35.0	42.2	59.8	90.1	87.9	81.8	61.9	51.5	44.0
$\frac{\text{pH final}}{\text{pH initial}}$	1.1	1.1	1.2	1.7	1.7	1.5	1.3	1.2	1.1

sorbent surface, the concentration of sorption solution and / or possibly other factors. In the present investigation, the equilibrium sorption by CP60 was undertaken using 180 mg/l (initial Cr(VI) concentration). A sorption maximum of 90.1 mg/g was determined at 303 K and pH 2.5 (Fig. 2). At initial pH < 2.5, Cr(VI) was hardly detected and Cr(III) was the main constituent of total chromium. A slight rise of the final pH was observed with low chromium sorption, (Table 3.) The final pH was low enough that protons compete with evolved Cr(III) ions for sorption at ion exchange sites such as - COOH and - OH. Table 3 reveals also that at initial pH 2.5, total chromium at equilibrium was minimal constituent Cr (VI) mostly with little or no Cr (III). This was associated with a considerable increase in the final pH and with the highest ratio of $\text{pH}_{\text{final}}/\text{pH}_{\text{initial}}$. These circumstances allowed most of evolved Cr (III) to be sorbed via ion-exchange and complexation. Within the initial pH 3.0-7.0, the sorption capacity decreased with the increase of the initial pH. However, no Cr (III) was detected in solution. Applying such relatively high pH values, Cr (VI) reduction is expected to decrease due to proton deficiency and thus little Cr(III) ions are evolved in solution. Accordingly, low chromium sorption is achieved even with an expected extent of physico-chemical adsorption of Cr(VI) within this pH [24]. Table 3 reveals also that the ratio $\text{pH}_{\text{final}}/\text{pH}_{\text{initial}}$ is the highest value when the initial applied pH was 2.5. This is associated with maximum chromium sorption which is probably due to ion exchange with the surface groups having exchangeable protons such as carboxylic and phenolic groups.

3.2.2. Kinetics of chromium removal

Kinetics of chromium removal and chromium sorption at 303 K by CP60, in the initial pH range 1.0-7.0 was relatively slow approaching equilibrium in 60-90 h (Fig. 3a, b). It is depicted that Cr(VI) concentration and total Chromium concentration decrease with time. However, in the initial pH range 1.0-2.5, the decrease in the concentration of Cr(VI) was faster. The difference between total chromium and Cr(VI) may account for unsorbed Cr(III) as a result of Cr(VI) reduction. Under such low pH, Cr (VI) may sorb without being reduced to Cr(III). This may explain the higher rate of Cr(VI) removal compared with that of total Cr sorbed (Fig. 3a).

The data obtained from the kinetic experiments were analyzed using two kinetic models, namely pseudo first order model and pseudo second order model [25], equations

(1) and (2)

$$\log C_t = \log C_o - \frac{K_1 t}{2.303} \quad (1)$$

$$\frac{1}{C_t} = \frac{1}{C_o} + K_2 t \quad (2)$$

where C_o and C_t are the concentrations of Cr(VI) at equilibrium and at time t , respectively. K_1 (hr^{-1}) is the pseudo first order rate constant and K_2 ($\text{l mg}^{-1} \text{hr}^{-1}$), is the pseudo second order rate constant for Cr(VI) removal.

In the initial pH range 3.0-7.0, there was no difference in concentration of Cr(VI) and total chromium, because Cr(III) was no more available in solution. Cr(VI) removal data were found to fit well pseudo first order model at initial pH 1.0-2.0, slightly less fitting at initial pH 2.5 and no fitting at

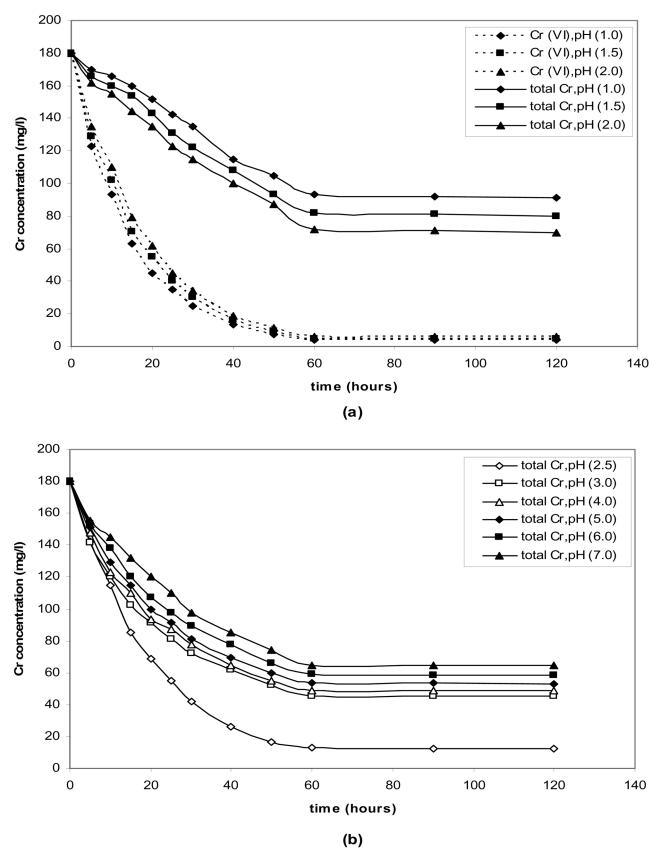


Fig. 3. Concentrations of Cr (VI) and total Cr versus time at different initial pH values. a) pH 1.0~2.0 and b) pH 2.5~7.0.

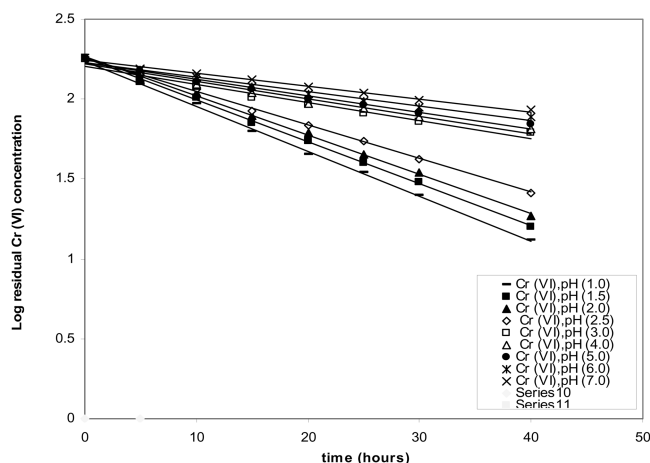


Fig. 4. Application of pseudo first order model for Cr (VI) removal at different initial pH.

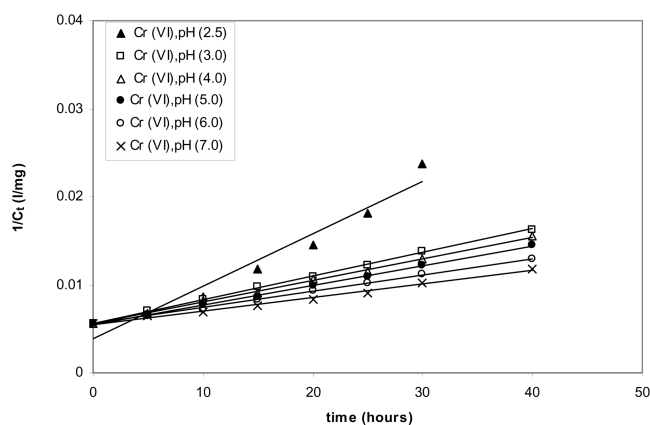


Fig. 5. Application of pseudo second order model for Cr (VI) removal at different initial pH.

initial pH 3.0-7.0, Fig. 4 and Table 4.

Being a solid, the carbon concentration is considered as constant and therefore the order of Cr(VI) removal depend on the proton concentration $[H^+]$ and on Cr(VI) concentration $[Cr(VI)]$. At initial pH 1.0, 1.5, and 2.0 the ratio $[H^+]/[Cr(VI)]$ equals 28.9, 9.13, and 2.9, respectively showing that $[H^+]$ is high enough to be considered as constant. Thus, at initial pH 1.0, 1.5 and 2.0, the removal of Cr(VI) follows pseudo first order kinetics. At initial pH 2.5, the ratio $[H^+]/[Cr(VI)]$ is 0.95 and this may explain the slight less fitting of the results of Cr(VI) removal at this particular pH, to pseudo first order model. Further increase of the initial pH to 3.0-7.0 is associated with continuous decrease of the ratio $[H^+]/[Cr(VI)]$ showing thus the dependence of the reaction kinetics on both $[H^+]$ and $[Cr(VI)]$, i.e. the reaction at this range of initial pH values would follow pseudo second order kinetics, Fig. 5 and Table 4.

3.2.3. Kinetics of chromium sorption

Table 4. Rate Constants of Cr (VI) Removal at Different Initial pH by CP60

Initial pH	Pseudo first order model $K_1(h^{-1})$	R^2	Pseudo second order model $K_2(l/mg\ hr)$	R^2
1.0	0.0647	0.9991	6.7×10^{-4}	0.865
1.5	0.0621	0.9984	5.9×10^{-4}	0.890
2.0	0.0595	0.9920	5.1×10^{-4}	0.898
2.5	0.0430	0.9691	4.7×10^{-4}	0.973
3.0	0.0267	0.9758	2.6×10^{-4}	0.999
4.0	0.0244	0.9730	2.4×10^{-4}	0.998
5.0	0.0230	0.9717	2.2×10^{-4}	0.999
6.0	0.0219	0.9724	2.0×10^{-4}	0.999
7.0	0.0198	0.9730	1.7×10^{-4}	0.994

For chromium sorption based on the decrease in total Cr concentration with time, two kinetic models were considered, pseudo first order model and pseudo second order models, equations 3, 4, respectively [26,27]

$$\log(q_e - q_t) = \log q_e - K_1' t / 2.303 \quad (3)$$

$$\frac{t}{q_t} = \frac{1}{K_2' q_e} + \frac{t}{q_e} \quad (4)$$

where q_e and q_t are the amounts of chromium sorbed at equilibrium and at time t (mg/g) respectively, K_1' (hr^{-1}) and K_2' ($g\ mg^{-1}\ hr^{-1}$) are the pseudo first order and pseudo second order rate constants: Here, the initial sorption rate $h = K_2' q_e^2$ (mg/g/h).

Fig. 6 shows that pH 2.5 is the optimum for maximum chromium uptake. At pH 2.5, Cr(III) develops in the early stage of sorption process and then slowly decreases almost to zero as equilibrium approaches. In the early stages, the protons released due to -COOH and -OH groups on the carbon surface. These protons compete with Cr(III) ions for ion exchange sites. As the reaction proceeds, more protons are consumed due to Cr(VI) reduction, and this allows evolved Cr(III) to be sorbed via ion exchange.

The isoelectric point (IEP) is an important parameter when charged species are sorbed from aqueous solution by carbonaceous sorbents [28]. IEP of the carbon sorbent CP60 was detected at pH 1.0, while pH_{PZC} was detected at pH 2.2. A decrease in the pH below pH_{PZC} means that both the surface of the sorbent and Cr(III) ions are positively charged and the uptake of metal ions is an exchange process of Cr(III) and protons [29]. However, the sorption maximum at pH 2.5 is not only related to the value of pH_{PZC} but mainly to the extent of Cr(VI) reduction and the rise of the final pH that allows the evolved Cr(III) to get sorbed via ion exchange.

Data of chromium sorption were found to fit well pseudo second order model (equation 4) in the whole pH range studied (Fig. 7). However, the data did not fit pseudo first order model (equation 3). K_2' , h and the correlation coefficient R^2 as determined by the application of equation 4 are

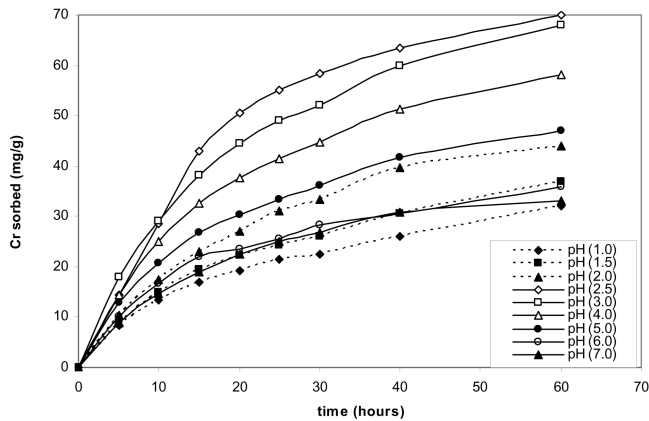


Fig. 6. Chromium sorption versus time at different initial pH.

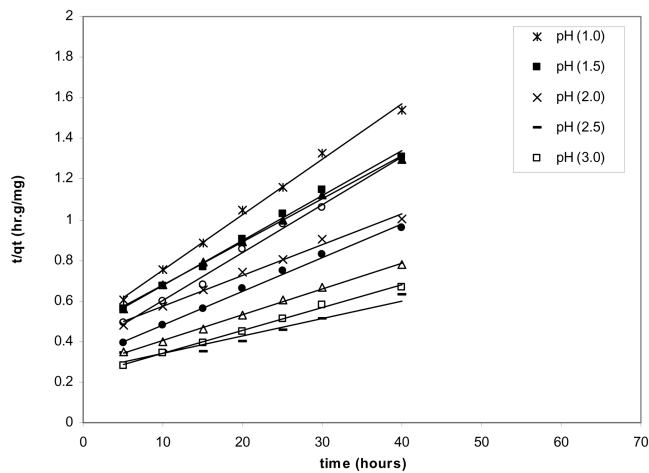


Fig. 7. Application of pseudo second order model for Cr sorption at different initial pH.

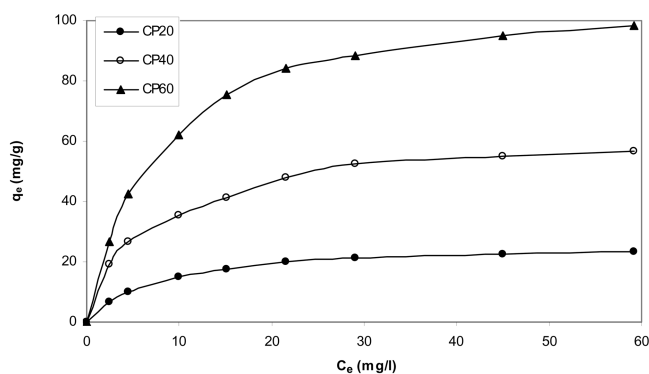


Fig. 8. Equilibrium adsorption isotherms of chromium at 30°C and pH 2.5 onto CP20, CP40 and CP60.

listed in Table 5. This indicates that the sorption of total chromium complies very well with pseudo second order reaction and an activated sorption mechanism, and the rate depends both on the sorbent and sorbate concentration [26].

Table 5. Kinetic Parameters of Chromium Sorption at 30°C on CP60 at Different Initial pH Values

Initial pH	q_e (mg/g)	K_2' (g/mg·h)	h (mg/g·h)	R^2
1.0	35.0	18.6×10^{-4}	2.28	0.9959
1.5	42.2	13.7×10^{-4}	2.44	0.9941
2.0	44.0	12.9×10^{-4}	2.50	0.9917
2.5	90.1	4.7×10^{-4}	3.85	0.9997
3.0	87.9	5.2×10^{-4}	4.00	0.9970
4.0	81.8	5.2×10^{-4}	3.45	0.9976
5.0	61.9	8.2×10^{-4}	3.13	0.9941
6.0	51.1	10.2×10^{-4}	2.71	0.9946
7.0	44.0	11.5×10^{-4}	2.22	0.9979

Table 5 depicts that the equilibrium sorption capacity increases with increase of the initial pH from 1.0 to 1.5 and further to 2.0 with the rise of the initial pH to 2.5, the increase of the equilibrium sorption capacity was very high. Thus, with the rise of the initial pH from 2.0 to 2.5, q_e increased from 44.0 to 91.1, i.e more than 2 fold increase. At initial pH 2.0, K_2' was the minimum and h was the maximum. Further rise in the initial pH to 3.0 was associated with small decrease in q_e , this decrease continues upon further increase of the initial pH.

It is now known that maximum chromium sorption at 30°C is obtained at initial pH 2.5 and that the sorption process of chromium onto CP60 approaches equilibrium within 60~90 h. This stimulated the study of chromium sorption at initial pH 2.5 and at 303 K using different initial concentration of Cr(VI) and allowing the equilibrium to be attained. Such equilibrium sorption isotherms are undertaken not only for the sorbent CP60 but also for less phosphoric acid-activated carbons, CP20 and CP40. In each experiment a fixed amount of the sorbent (0.1 g) was contacted with 50 ml of an aqueous solution of Cr(VI) of varying initial concentration 20~180 mg/l. The initial pH was adjusted at 2.5 and the glass stoppered 100 ml capacity bottles containing the resulting mixtures were left for 90 h with occasional shaking. After this time, the contents of the bottles were filtered and the equilibrium concentration C_e (mg/l) of total chromium was determined and the chromium uptake q_e (mg/g) was calculated.

Fig. 8 shows the equilibrium sorption isotherms of chromium onto CP20, CP40 and CP60, at 303 K and with initial pH 2.5. The isotherms are of L-type according to Giles's classification [30]. The Langmuir equation [31] was used to analyze the chromium sorption data. Equation 5 is the linear form of Langmuir equation:

$$\frac{C_e}{q_e} = \frac{1}{bq_m} + \frac{C_e}{q_m} \quad (5)$$

C_e and q_e have been previously defined, q_m is the maximum sorption capacity (mg/g) which is usually called,

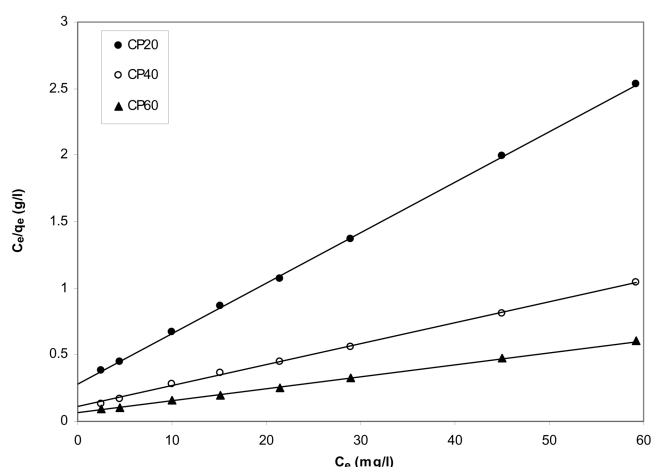


Fig. 9. Linear Langmuir plots for chromium sorption at 30°C and pH 2.5 onto CP20, CP40 and CP60.

Table 6. Modeling of Equilibrium Chromium Sorption at 30°C and Initial pH 2.5 Onto CP20, CP40 and CP60

Sorbent	q_m (mg/g)	b (l/mg)	R^2
CP20	29.5	11.3×10^{-2}	0.9979
CP40	73.9	10.8×10^{-2}	0.9991
CP60	123.0	4.1×10^{-2}	0.9984

the monolayer capacity, and b (l/mg) is a constant related to the sorption energy. These sorption parameters were obtained from the linear Langmuir plots shown in Fig. 9. Table 6 gives the q_m and b values together with the values of R^2 for chromium sorption onto CP20, CP40 and CP60. Fig. 9 and Table 6 depict that the equilibrium sorption of chromium fits very well the Langmuir equation. q_m increases with the increase of the concentration of the phosphoric acid used in carbon activation. The increase of the concentration of phosphoric acid probably increases the surface acidity via creation of carbon-oxygen groups of acidic nature.

Trials have been made to relate the sorption capacity of the carbon sorbents to some of its surface parameters. These trials led to the following observations. (i) chromium sorption increased with the decrease of the surface pH and pH_{PZC} of the carbon sorbent (ii) chromium sorption increased with the increase of surface acidity of the carbon sorbent particularly of the surface acidic group having exchangeable protons such as carboxylics and phenolics.

4. Conclusions

Phosphoric acid activated carbons are characterized by high specific surface area and total porosity with these textural parameters increased with the increase of the strength of phosphoric acid used in activation. Phosphoric acid activated carbons are of acidic nature as indicated by

their surface pH and their pH_{PZC} being in the acid range.

Removal of Cr(VI) via sorption onto chemically activated carbons involves reduction to Cr(III) at solution pH 2.5. Maximum sorption of chromium was always determined from chromium solution at pH 2.5. Removal of chromium follows first order kinetic at pH 2.5 and second order kinetic beyond this pH. Sorption of chromium is related to the surface pH of the carbon sorbent and the concentration of the carbon-oxygen groups of acid type on the carbon surface, particularly those having exchangeable protons.

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