

# Removal of hexavalent chromium from aqueous solutions by granular activated carbon

DC Sharma\* and CF Forster\*

School of Civil Engineering, The University of Birmingham, Edgbaston, Birmingham B15 2TT

## Abstract

Batch adsorption trials were used to assess the effectiveness of using activated carbon as a sorbent for the removal of hexavalent chromium from solution. The results show that, although the pH for maximum efficiency varied slightly with the concentration of Cr(VI) being applied, the most effective pH was in the range 2.5 to 3.0. Based on linear regression analysis, the data obtained from the batch studies showed a good compliance with both the Langmuir and the Freundlich equations. The values obtained for the isotherm constants showed that the maximum adsorption capacity,  $X_m$ , was 145 mg/g. An examination of the adsorption kinetics was also made and an analysis of the data shows that pore diffusion is not the only factor governing the sorption rate.

## Nomenclature

$C_e$	: equilibrium concentration (mg/l)
$C_o$	: initial concentration (mg/l)
$K_1$	: forward kinetic constant (mol/s)
$K_F$	: Freundlich constant (mg/g)
$n$	: Freundlich constant
$K_r$	: rate factor
[M]	: concentration of free metals in solution (mol/l)
[P]	: concentration of binding sites (mol/l)
[PM]	: concentration of metals bound to carbon (mol/l)
$q_e$	: adsorption density (mg chromium/g activated carbon)
$W_s$	: carbon dose (g/l)
$X_m$	: Langmuir constant (mg/g)
$k$	: Langmuir constant (l/mg)

## Subscripts

init	: initial value
fin	: final value
lim	: equilibrium value

## Introduction

Waste waters containing chromium are generated by a number of industries, for example, metal plating and tanning. Chromium may also be found in cooling tower blow-downs. Although chromium can exist in a number of oxidation states, industrial effluents are most likely to contain the trivalent, Cr(III), or the hexavalent, Cr(VI), forms. Of the two, the hexavalent form is generally thought of as being the more toxic (Coleman and Paran, 1991). Environmental legislation within the member states of the European Community has, over the last decade, imposed increasingly rigorous

standards on discharges to the environment and for the concentrations of the more significant pollutants in both natural and treated waters. For example, the maximum concentration permitted in drinking water by the United Kingdom Water Supply (Water Quality) Regulations 1989 is 0.05 mg/l. Similarly, the concentrations of total chromium in surface waters which are to be abstracted for potable supply are restricted to a maximum value of 0.075 mg/l by an EC Directive (Mance et al., 1984). It is, therefore, essential that chromium-rich waste waters are treated adequately and discharges of chromium to the aquatic environment are minimised.

Reduction/precipitation is probably the most commonly used technique for the treatment of industrial effluents containing chromium (Wild, 1987). However, it is a process which can give an incomplete removal, has a high chemical requirement and produces a voluminous, toxic sludge which may pose disposal problems. Because of this, a variety of other treatment technologies have been evaluated. These have included ion exchange (Neville, 1994) and adsorption with naturally occurring products (Tan et al., 1993; Sharma and Forster, 1993) or activated carbon (Lee and Low, 1989; Huang and Wu, 1975). The use of activated carbon certainly does not require the regular use of chemicals, but obviously the question of disposal must be considered, as must the costs of any regeneration stage. Nevertheless, activated carbon must be thought of as the material which sets the standard for adsorption and as such its role in removing chromium from waste-water streams, either as a complete treatment or as a final "polishing", has been examined previously (for example, Kim and Zoltek, 1977; Bowers and Huang, 1981). The results which have been reported are very variable, particularly in terms of the optimum pH for chromium removal. Faust and Aly (1987) have reported that the greatest removal was achieved at pH values of 5 to 6 whereas other workers have noted that the best results were achieved at lower pH values ( $\leq 2.5$ ) (Huang and Wu, 1975; Huang and Bowers, 1979).

In developing countries, pollution control measures frequently need to be based on lower-cost technologies. In this context, one area which is being explored is the use of naturally occurring materials which have the potential for adsorbing pollutants. These have included low-cost biosorbents, such as pine bark (Vascoucelos and Beca, 1994) and coconut husk fibre (Tan et al., 1993), and activated carbons produced from low-cost or waste materials have

\* Current address: Central Pollution Control Board, Delhi

\* To whom all correspondence should be addressed.

☎ (0944)0121 4145069; fax: (0944) 0121 4143675;

e-mail: forster@bham.ac.uk

Received 5 May 1995; accepted in revised form 5 January 1996.

been studied (Gaid et al., 1994). In judging such material, consideration must be given to local factors such as cost and availability of the product, but also the adsorption should be measured against a standard, activated carbon. This paper reports data for the removal of chromium from aqueous solution by a granular activated carbon as part of a wider study into low-cost adsorption.

## Materials and methods

The activated carbon used in this study was Filtrasorb 400 (Chemviron Limited, London). Its general characteristics are shown in Table 1. The carbon was dried in large trays in an oven at 110°C for a period of 24 h and then packed into screw-top bottles for future use.

TABLE 1 CHARACTERISTICS OF FILTRASORB 400 (DATA FROM CHEMIRON LTD.)	
Mean particle dia. (mm)	0.9 - 1.1
Surface area (m <sup>2</sup> /g)	1 050 - 1 200
Pore size (Å)	5.5 - 6.5
Pore volume (cm <sup>3</sup> /g)	0.85 - 0.95

All the solutions were prepared from certified reagent grade chemicals. Potassium dichromate (K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>) (BDH Limited, Poole, England) was used as the source of hexavalent chromium. Standard acid and base (H<sub>2</sub>SO<sub>4</sub> and NaOH) were used for the pH adjustments. Stock chromium solutions (1 000 mg/l) were prepared using distilled water and all further working solutions were made by diluting the stock solution.

Batch sorption experiments were conducted in a constant temperature room (25°C) on a rotary shaker (100 r/min) using 500 ml screw-top conical flasks. In the adsorption isotherm tests the reaction mixture consisted of a total volume of 250 ml containing 2 g/l of activated carbon. Eight tests were performed with initial pH values (pH<sub>init</sub>) of 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0 and 10.0, varying the initial hexavalent chromium concentrations (C<sub>0</sub>) from 20 mg/l up to 1 000 mg/l. After shaking the flasks for 24 h, the reaction mixture was filtered through Whatman filter paper (No. 1). The final pH (pH<sub>fin</sub>) of the filtrate was measured together with the hexavalent chromium and total chromium concentrations. In the sorption kinetics experiments, the carbon dose (W<sub>c</sub>) was fixed at 4 g/l, the initial chromium concentrations at 100, 200, 300 and 400 mg/l and the pH was adjusted to 2.5. Each flask was removed after the required contact time, the reaction mixture was filtered and the filtrate was analysed as described previously. Tests into the effect of sorbent doses were conducted at an initial concentration (C<sub>0</sub>) of 200 mg/l at pH<sub>init</sub> values of 1.5, 2.0, 2.5 and 3.0 respectively, whilst varying the carbon doses (W<sub>c</sub>) from 2 g/l up to 16 g/l. The effect of varying initial chromium concentration (C<sub>0</sub>) was studied at pH 2.5 with chromium concentrations ranging from 100 mg/l up to 400 mg/l.

Hexavalent chromium was analysed by the purple-violet coloured complex developed between 1-5 diphenyl carbazide and chromium (VI) ions in acidic solution (Standard Methods, 1985). The total chromium was determined by oxidising any trivalent chromium with potassium permanganate, followed by analysis as

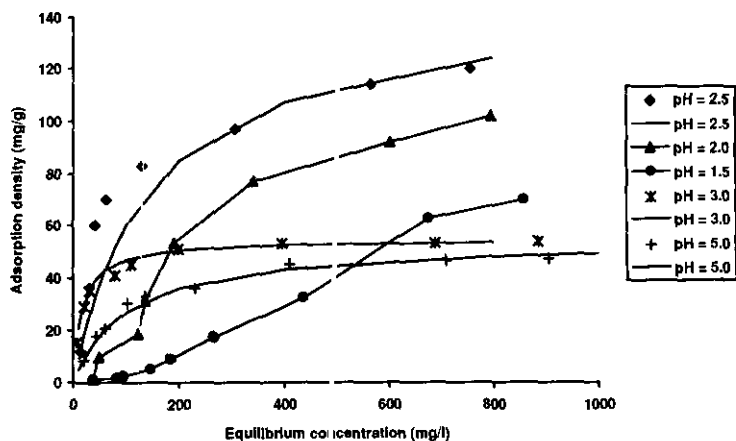


Figure 1  
Typical adsorption data together with the curves derived from the Langmuir equation

hexavalent chromium. The difference between total and hexavalent chromium concentrations gave the concentration of trivalent chromium.

## Results and discussion

### Sorption equilibria

Sorption equilibrium is established when the concentration of adsorbate in the bulk solution is in dynamic balance with that of the interface. Figure 1 shows the experimental data for the chromium - activated carbon system together with the isotherms calculated from the Langmuir equations derived from these data.

A sharp decline in adsorption densities can be seen at pH values above and below 2.5, indicating that pH 2.5 is the optimum pH for the adsorption in an unbuffered system. This is a similar result to that reported previously by Bowers and Huang (1981). At very low initial chromium concentrations it is clear from the same figure that at pH 1.5 and 2.0 there is almost no adsorption of chromium ions onto the activated carbon. This is most likely to be due to the rapid reduction of the hexavalent form to give cationic forms of chromium which do not adsorb well. The data also show that there is little adsorption at high pH. The reason for this is the change in the surface charge of the carbon at pH values greater than about 7.

Linearisation of the isothermal data by substituting the required equilibrium concentrations in the Langmuir equation indicated strong positive correlations between the parameters at pH 2.5 and above, but failed to do so at lower pH values. The low values of the correlation coefficients at pH 1.5 and 2.0 indicated that the adsorption did not follow the Langmuir equation (Table 2). The constant X<sub>m</sub>, which is indicative of the maximum adsorption capacity, decreased as the pH increased, from a value of 145 mg/g at pH 2.5 to one of 6.47 mg/g at pH 10. The adsorption data did comply with the Freundlich equation over the entire pH range. However, the correlation coefficient tended to be lower. The Freundlich constants (K<sub>F</sub> and 1/n) did not show any trend with increasing solution pH.

### pH dependence of chromium removal

The effect of varying initial chromium concentration (C<sub>0</sub>) and pH<sub>init</sub> on the efficiency of treatment is shown in Figs. 2 and 3. When only hexavalent chromium removal is considered (Fig. 2), it can be seen that at low pH values (1.5 and 2.0) there was a very high removal of chromium at the lower starting concentrations but that, as the

pH <sub>adj</sub>	Langmuir constants			Freundlich constants		
	X <sub>m</sub> (mg/g)	k x 10 <sup>-5</sup> (l/mg)	Correlation (r <sup>2</sup> )	K <sub>F</sub> (mg/g)	(1/n)	Correlation (r <sup>2</sup> )
1.5	-	-	0.325	0.00253	1.553	0.973
2.0	-	-	0.131	0.00293	1.715	0.883
2.5	145.0	07.1	0.88	3.13	0.611	0.717
3.0	54.35	63.1	0.999	14.70	0.211	0.781
4.0	54.5	14.6	0.998	3.04	0.458	0.862
5.0	53.76	10.2	0.997	2.085	0.508	0.879
6.0	49.02	7.16	0.988	1.043	0.603	0.817
10.0	6.47	1.92	0.907	5.602	3.828	0.647

initial concentration of chromium increased, its removal decreased. At higher pH values there was a steady decrease in the removal as the initial chromium concentration increased.

When total metal removal is considered (Fig. 3), there was a slightly different pattern of behaviour. The data show that there is a very definite pH value for the optimum removal which depends on the initial concentration. In interpreting these results, it must be recognised that two quite distinct processes are involved; the reduction of hexavalent chromium and adsorption; and the increasing dominance of the reduction process as the pH decreases. This, in turn will alter the amount of adsorption which occurs. The reduction of hexavalent chromium has been examined previously and, according to Kim and Zoltek (1977), the optimum removal of chromium occurs when the [proton : chromium (VI)] ratio is 1:1. A ratio of > 1 is indicative of the reduction stage being predominant whilst a ratio of less than one indicates incomplete adsorption. Using the data in Fig. 3, values for the [proton: chromium(VI)] ratio at the optimum chromium removal were calculated. These ranged from 2.6 at an initial chromium concentration of 20 mg/l to 0.16 when the initial concentration was 1 000 mg/l. In other words, a 1:1 ratio is not necessarily the general condition for optimum removal. Similar results have been reported by Huang and Bowers (1979).

The equilibrium pH (pH<sub>fin</sub>) at the end of the reaction at different initial chromium concentrations and pH (pH<sub>ini</sub>) are shown in Fig. 4. In general, it is seen that the pH of the reaction mixture was always raised after the adsorption reaction when the system was not buffered at very low or very high pH. This indicated that the activated carbon was alkaline in nature and hydroxyl ions were released into the solution during the adsorption reaction. The increase in solution pH could not be seen at very low pH, because of the high concentrations of hydrogen ions.

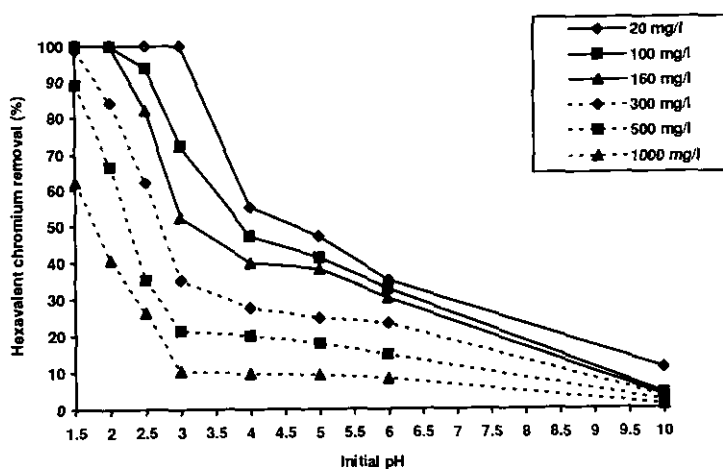


Figure 2  
The effect of varying the initial pH on the removal of hexavalent chromium with an adsorbent dose of 2 g/l

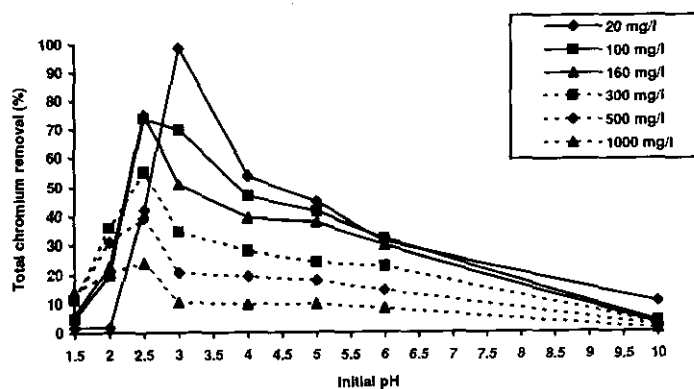
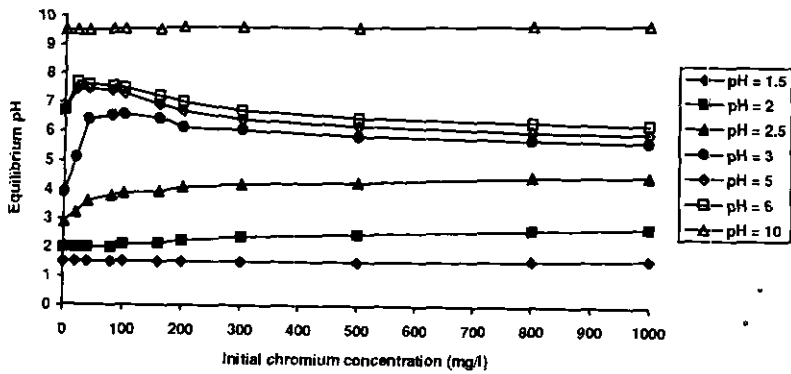
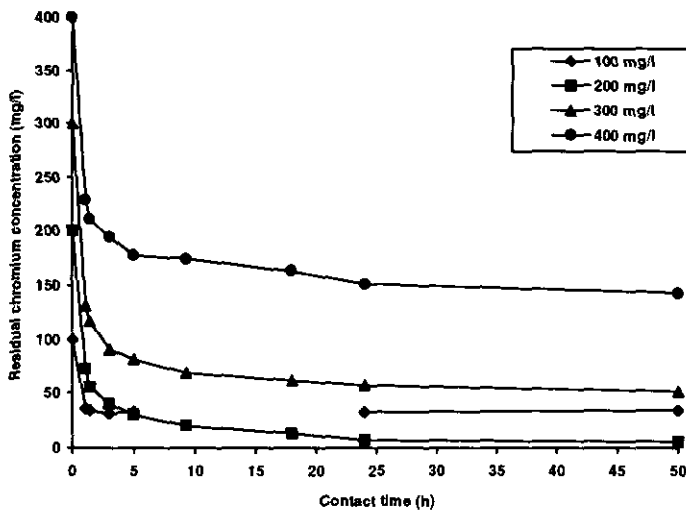


Figure 3  
The effect of varying the initial pH on the total chromium removal by an adsorbent dose of 2 g/l



**Figure 4**

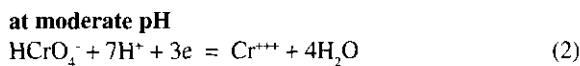
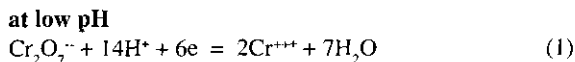
The effect of the initial chromium concentration on the equilibrium



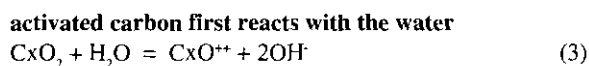
**Figure 5**

The effect of contact time on the residual chromium concentration for a series of initial concentrations at a pH of 2.5 and an adsorbent dose of 4 g/l

The removal of hexavalent chromium ions at very low pH is mainly governed by the active reduction reaction given by the following equations:

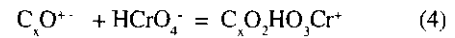


Therefore, more Cr(VI) ions are reduced to Cr(III) as the pH is reduced. It is also seen from these equations that both of these reactions are proton consuming, thus giving rise to an increase in solution pH. According to Huang and Wu (1975), the "oxo" groups ( $\text{C}_x\text{O}$  and  $\text{C}_x\text{O}_2$ ) formed on the carbon surface during the activation at very high temperatures are mainly responsible for the adsorption of anions from the solution. This can be shown as:

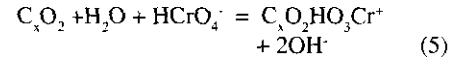


As a result of this,  $\text{OH}^-$  ions are released into the solution which increase the pH. Figure 4 indicates that the pH of the distilled water was increased to 6.8, when the carbon (2 g/l) was introduced at  $\text{pH}_{\text{init}} 4$ .

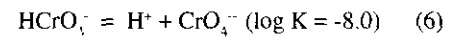
The reaction between chromium ions and the carbon surface can be expressed as:



By combining Eqs. (3) and (4) the overall reaction scheme is obtained.



Thus, every mole of bichromate ion adsorbed results in the release of two moles of hydroxyl ions which eventually raise the solution pH. This increase in pH was observed throughout the experiments, except with the higher chromium concentrations and pH values between pH 3.0 and 6.0 where the increasing concentrations ( $C_0$ ) showed a very slight decreasing trend in solution pH (Fig. 4). This could perhaps be due to the fact that the unadsorbed bichromate ions at higher solution pH (6.5 and more) change into chromate ions releasing protons into the solution as shown below (Sengupta et al., 1988):



The release of hydrogen ions into the solution thus decreases the equilibrium pH at higher chromium concentrations. This supports the philosophy that chromate ions do not effectively take part in the adsorption reaction and remain unadsorbed.

### Kinetics of adsorption

The kinetics of chromium sorption were studied at varying chromium concentrations at  $\text{pH}_{\text{init}} 2.5$  and the results are shown in Fig. 5. It is clear from this that most of the chromium ions were adsorbed during the first 5 h. However, the equilibrium for  $C_0 = 100 \text{ mg/l}$  was achieved more quickly than with higher initial chromium concentrations. This was mainly due to the fact that at this chromium concentration the final pH always stayed below 3.8. At this pH, the reduction reaction was quite active and all the remaining hexavalent ions were reduced to the unadsorbed trivalent form. This can be seen from an examination of Fig. 6 which reveals that, at concentrations of more than 200 mg/l, the amount of chromium which was reduced, decreased significantly at contact times of more than 5 h. However, when the initial concentration was 100 mg/l, it can be seen that reduction continues throughout the test period. This suggests that the equilibrium time is not independent of the initial concentrations, probably because the intraparticle diffusion was not predominant. A decreasing removal rate, particularly towards the end, indicates a possible monolayer of Cr(VI) ions on the outer interface of the film due to continuous agitation maintained during the experiment.

An expression which enables the adsorption kinetics to be calculated has been developed by Gosset et al. (1986). This

involves plotting ( $K_1 t$ ) against time ( $t$ ) to derive values of  $K_1$ :

$$K_1 t = \frac{1}{[PM]_{lim} - [M]_{init}} \cdot \ln \frac{[M]_{init}}{[PM]_{lim}} \cdot \frac{[PM]_{lim} - [PM]}{[M]_{init} - [PM]} \quad (7)$$

In other words, the chromium removal follows a second-order reaction involving the concentrations of both the chromium and the carbon.

The data in Table 3 show that the concepts developed by Gosset et al. (1986) are applicable to the chromium/carbon system and that the forward kinetic constant  $K_1$  was found to increase with decreasing chromium concentrations.

The linearised  $K_1$  and  $C_0$  values on a log-log plot showed a correlation coefficient ( $r^2$ ) as high as 0.994 indicating a strong relationship between the parameters given as:

$$K_1 = 20.15 C_0^{-3.0} \quad (8)$$

Equation (7) can be rearranged. Then, substituting the value of  $K_1$  from Eq. (8) and putting:

$$[M]_{eq} = [M]_{init} - [PM]_{lim}$$

$$[PM] = [M]_{init} \cdot \frac{\exp([M]_{eq} 20.15 ([M]_{init}^{-3.0} t)) - 1}{\frac{[M]_{init}}{[M]_{init} - [M]_{eq}} \cdot \exp([M]_{eq} 20.15 ([M]_{init}^{-3.0} t)) - 1} \quad (9)$$

where  $[M]_{eq}$  is the equilibrium metal concentration in the solution.

Equation (9) can thus be used to calculate the concentrations of chromium ions adsorbed at any given time and any initial concentration within the limits of the test conditions.

The log-log plot between the percentage chromium removal ( $R$ ) and time ( $t$ ) indicated a strong positive relationship (except at  $C_0 = 100$  mg/l):

$$R = K_1 t^b \quad (10)$$

Here  $b$ , which is the slope of the line, depicts the strength of adsorption mechanism (Srivastava et al., 1987) and  $K_1$  may be taken as a rate factor (ie percent solute removal per ( $t = 1$ )). Higher values of  $K_1$  indicate an enhancement in the rate of removal, whereas larger  $b$  values indicate an improved bonding between solute ions and sorbent particles. The results of this analysis are shown in Table 3, and clearly indicate that  $K_1$  values increased with decreasing chromium concentrations ( $C_0$ ) up to 200 mg/l, below which it again showed a decreasing trend, for the reason that the reduction reaction predominates at lower concentrations (and low pH). The values of the slope  $b$  were always found to be less than or equal to 0.1. According to Weber and Morris (1963) a value of  $b = 0.5$  reflects "intraparticle diffusion" as the rate-determining step. The uptake of hexavalent chromium by activated carbon generally involves three stages. One is the transport of the ions to the surface of the carbon, the second is the diffusion of the ions into the internal structure of the carbon and the third is the adsorption/reduction processes which occur at both the internal and external surfaces. Huang

and Bowers (1979) have shown that reduction only predominates at the external surfaces whilst adsorption is predominant in the pores. They also stated that, although mixing and external mass transfer could be rate-limiting for the reduction process, it would not affect adsorption as long as the rate of transfer to the surface was greater than the rate of adsorption. This current study, in which the values for  $b$  were less than or equal to 0.1, shows that the sorption rates are controlled by a range of factors and not just by intraparticle diffusion. It is thought that the reasons for this are related to:

- the relative sizes of the ions and the pores
- the changes which occur in the electrostatic attraction between the ions and the carbon as the pH is altered.

### Effect of carbon doses on adsorption

The effect of carbon doses on adsorption densities at different initial pH values and chromium concentrations ( $C_0$ ) is shown in Figs. 7 and 8 respectively.

In general, the adsorption densities were found to decrease with increasing carbon doses, as at higher carbon doses, the carbon does not become fully saturated due to the increased solution pH (Table 4). At an initial chromium concentration of 200 mg/l the adsorption densities were found to be maximum at pH 2.5 with relatively lower values on either side of this pH (Fig. 7). The adsorption densities were also observed to increase with increasing initial chromium concentration ( $C_0$ ) at  $pH_{init}$  2.5.

The linearisation of these data on a log-log plot indicated very high correlation coefficients (more than 0.98), the relationship being:

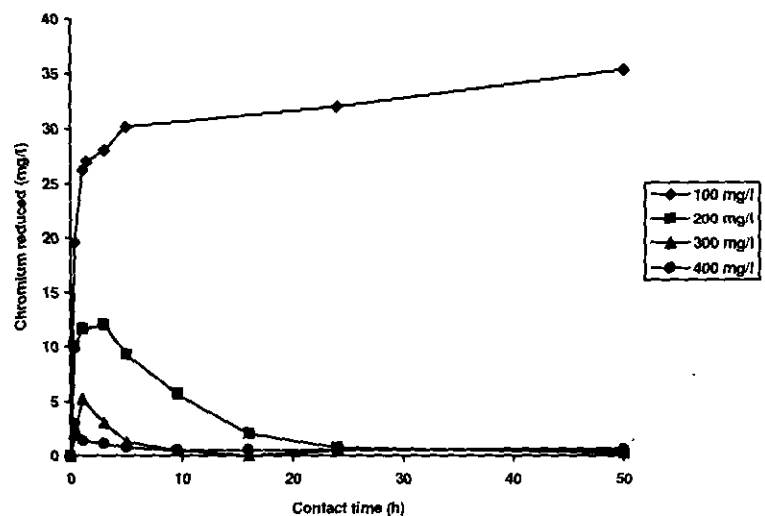
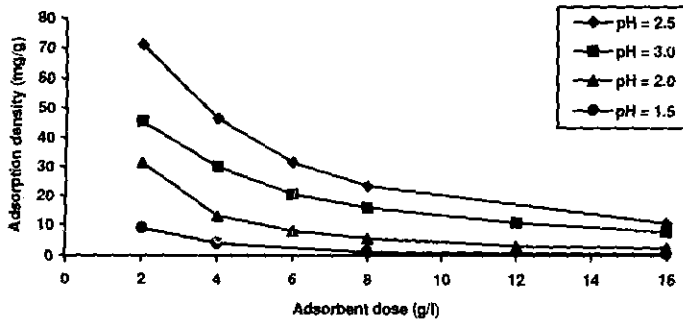
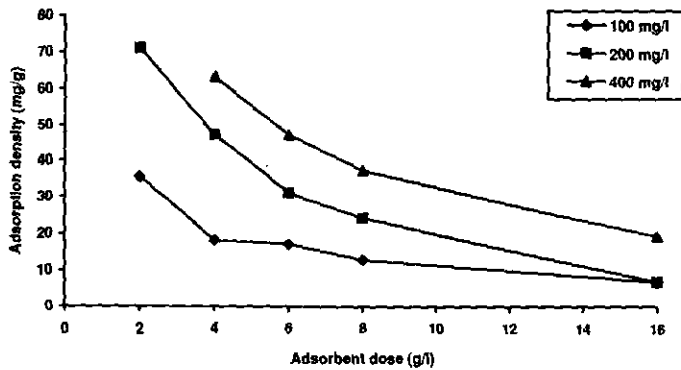


Figure 6  
The effect of contact time on chromium reduction with an adsorbent dose of 4 g/l

TABLE 3 KINETICS CONSTANTS OF ADSORPTION					
$C_0$ (mg/l)	$K_1$ ( $\text{mol}^{-1} \cdot \text{s}^{-1}$ )	Correlation ( $r^2$ )	$K_1$	$b$ ( $\text{s}^{-1}$ )	Correlation ( $r^2$ )
100	2.672	0.94	63.83	0.04	0.39
200	0.372	0.98	70.6	0.10	0.979
300	0.123	0.97	61.23	0.10	0.973
400	0.038	0.97	47.0	0.09	0.98



**Figure 7**  
The relationships between adsorbent dose and adsorption density at a series of initial pH values ( $C_o = 200 \text{ mg/l}$ )



**Figure 8**  
The effect of adsorbent dose on adsorption density at series of  $C_o$  values and an initial pH of 2.5

$$q_e = a(W_s)^m \quad (11)$$

where,  $a$  and  $m$  are the intercepts and slopes of the regression lines. The values of  $a$  and  $m$  for varying pH and chromium concentrations are shown in Table 5. The constant  $a$  was found to increase with increases in the chromium concentration ( $C_o$ ), but showed a decreasing trend on either side of  $\text{pH}_{\text{int}}$  at 2.5. The constant  $m$ , however, showed an insignificant variation with varying chromium concentrations.

The chromium removal efficiencies at varying carbon doses are given in Figs. 9 and 10 and clearly show that at low pH, the higher carbon doses act adversely in adsorption, perhaps making more carbon

available for an active reduction reaction. Once again, the maximum efficiency of chromium adsorption was observed at pH 2.5. Figure 10 clearly shows that the carbon doses of 4 g/l gave maximum efficiency of treatment at  $C_o = 200 \text{ mg/l}$ . It is, therefore, suggested that doses of 4 g/l at pH 2.5 would be optimum at  $C_o = 200 \text{ mg/l}$ , if maximum removal and adsorption are to be achieved.

### Comparison with other studies

The experimental results as reported by Huang and Wu (1977) on the same material (Filtrisorb 400) indicated the maximum adsorption capacity ( $X_m$ ) of the order of 57.7 mg/g of carbon at an equilibrium pH 6.0. The results of this present study show a maximum adsorption capacity of the order of 145 mg/g in the equilibrium pH range between 3.3 to 4.0. This large difference in adsorption capacity could be due to the fact that they used carbon doses of 10 g/l (against 2 g/l in the present study) in a total volume of 50 ml (against 250 ml in the present case). Such a high carbon dose must have caused a greater shift in solution pH, thus not attaining the optimum conditions for adsorption. Moreover, the highest chromium concentration used in the study was only 250 mg/l (as against 1000 mg/l in this case), and it is quite likely that the carbon during the isotherm studies was not fully saturated. The experimental results on sphagnum moss peat (Sharma and Forster, 1993) are in agreement with the present investigation, with the exception that peat was found to be acidic in nature and acted as a buffering agent during the adsorption reaction. The maximum adsorption capacity at pH 1.5 was observed to be 119 mg/g which is quite comparable to that of activated carbon. The forward kinetic constants of activated carbon were much higher than reported for moss peat, due to the obvious reason that activated carbon is highly porous and possesses almost five times more surface area when compared with moss peat.

As most of the electroplating units discharge waste waters in acidic solution of pH 2.5 to 3.0, the pH correction step is automatically eliminated if activated carbon were to be used for chromium adsorption on an industrial basis. Any unadsorbed trivalent chromium ions could be easily removed in another activated carbon column along with other cations such as  $\text{Ni}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Zn}^{2+}$  and  $\text{Cd}^{2+}$  as these ions are reported to be best removed at moderate to high pH. In this regard, activated carbon also helps in increasing the solution pH, when Cr(VI) ions are adsorbed onto it. Thus, the requirement of alkali for pH correction is also eliminated.

Carbon dose ( $W_s$ , mg/l)	$C_o = 200 \text{ mg/l}$				pH = 2.5	
	$\text{pH}_{\text{int}}$ 1.5	$\text{pH}_{\text{int}}$ 2.0	$\text{pH}_{\text{int}}$ 2.5	$\text{pH}_{\text{int}}$ 3.0	$C_o = 100 \text{ mg/l}$	$C_o = 400 \text{ mg/l}$
	2.0	1.5	2.25	4.10	6.20	3.85
4.0	1.5	2.40	5.90	7.30	4.40	6.0
6.0	-	2.50	6.70	7.7	5.30	6.40
8.0	1.5	2.60	7.0	7.9	6.30	6.80
12.0	-	2.75	-	8.1	-	7.30
16.0	1.5	3.0	7.70	8.2	6.65	7.60

In the light of high material cost it is, however, recommended that regeneration and reuse of chromium laden activated carbon must be thoroughly investigated, as the exhausted carbon cannot be discarded in a once through treatment. In this regard sodium hydroxide solution could prove to be a good regenerant.

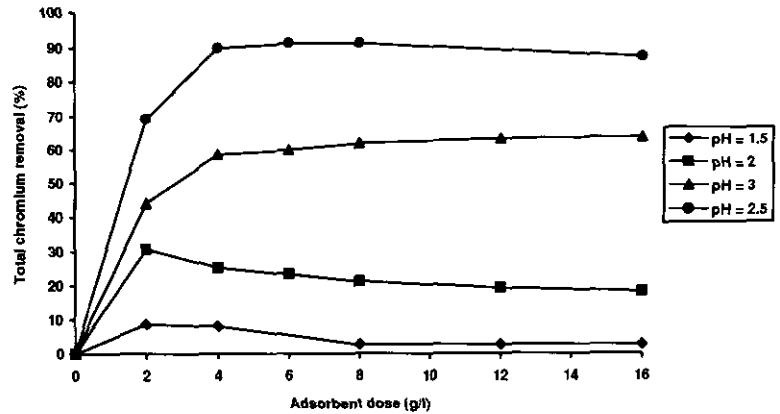
### Conclusions

- Activated carbon (Filtrisorb 400) is a suitable adsorbent for the removal of chromium(VI) where it acts as a reducing, adsorbing and neutralising substance in the acidic solution.
- At pH 2.5 and above, the carbon-chromium system followed Langmuir isotherms, with maximum adsorption capacity of 145 mg/g carbon.
- The kinetic batch reaction rates are highly favourable, the forward kinetic constants showing a logarithmic increasing trend with decreasing chromium concentrations. Pore diffusion does not seem to be the only rate-controlling step.
- Carbon doses of more than 4g/l do not enhance the scavenging of Cr(VI) ions from the solution. Rather, they cause a hindrance to adsorption of Cr(VI) ions when the solution pH is very low.
- Optimum levels of treatment are achieved when 200 mg/l of Cr(VI) is treated at pH 2.5 with a carbon dose of 4 g/l.

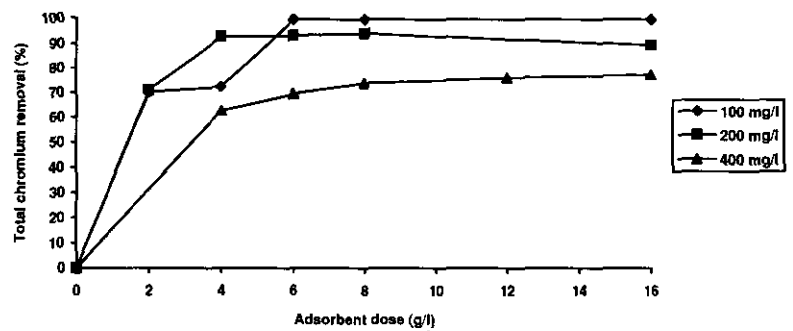
### References

BOWERS AR and HUANG CP (1981) Activated carbon process for the treatment of chromium (VI) containing industrial wastewaters. *Water Sci. Technol.* **23** 629-650.  
 COLEMAN RN and PARAN JH (1991) Biofilm concentration of chromium. *Environ. Technol.* **12** 1079-1093.  
 FAUST SD and ALY OM (1987) *Adsorption Processes for Water Treatment*. Butterworths.  
 GAID A, KAOUA F, MEDERRES N and KHODJSA M (1994) Surface mass transfer processes using activated date pipes as adsorbent. *Water SA* **20** 273-278.  
 GOSSET T, TRANCART JL and THEVENOT DR (1986) Batch metal

removal by peat: Kinetics and thermodynamics. *Water Res.* **20** 21-26.  
 HUANG CP and BOWERS AR (1979) Activated carbon process for the treatment of wastewaters containing hexavalent chromium. *EPA - 600/2 - 79-130*.  
 HUANG CP and WU MH (1975) Chromium removal by carbon adsorption. *J. Water Pollut. Central Fed.* **47** 2437-2442.  
 HUANG CP and WU MH (1977) The removal of chromium (VI) from dilute aqueous solution by activated carbon. *Water Res.* **11** 673-679.  
 KIM JI and ZOLTEK J (1977) Chromium removal with activated carbon. *Prog. Water Technol.* **9** 143-155.  
 LEE CK and LOW KS (1989) Removal of copper from solution using moss. *Environ. Technol. Letters* **10** 395-404.  
 MANCE G, BROWN VM, GARDINER J and YATES J (1984) Proposed Environmental Quality Standards for List II Substances in Water: Chromium. WRC Technical Report TR207.  
 NEVILLE M (1994) The removal and recovery of heavy metal ions from industrial effluents. Paper presented at Conf. on Industrial Wastewater Treatment, Manchester, UK.  
 SENGUPTA AK, SUBRAMONIAN S and CLIFFORD D (1988) More on mechanisms and some important properties of chromate ion. *J. Environ. Eng. ASC* **114** 137-153.  
 SHARMA DC and FORSTER CF (1993) Removal of hexavalent chromium using sphagnum moss peat. *Water Res.* **27** 1201-1208.  
 SRIVASTAVA SK, PANT N and PAL N (1987) Studies on the efficiency of a local fertilizer waste as a low cost adsorbent. *Water Res.* **21** 1389-1394.  
 STANDARD METHODS (1985) *Standard Methods for the Examination of Water and Wastewater* (16th edn). APHA, AWWA, WPCF, Washington DC.



**Figure 9**  
The effect of adsorbent dose on the total chromium removal with an initial concentration of 200 mg/l



**Figure 10**  
The effect of adsorbent dose on the total chromium removal with an initial pH of 2.5

TABLE 5 EFFECT OF INITIAL pH AND CHROMIUM CONCENTRATION (C <sub>0</sub> ) ON THE ADSORPTION				
C <sub>0</sub> (mg/l)	pH <sub>init</sub>	a	m	Correlation (r <sup>2</sup> )
200	1.5	32.2	-1.696	0.98
200	2.0	73.9	-1.246	0.99
200	2.5	145.4	-0.895	0.98
200	3.0	87.8	-0.838	0.99
100	2.5	65.94	-0.822	0.99
200	2.5	145.4	-0.895	0.98
400	2.5	209.3	-0.852	0.99

TAN WT, OOI ST and LEE, CK (1993) Removal of chromium (VI) from solution by coconut husk and palm-pressed fibres. *Environ. Technol.* **14** 277-282.

VASCOUCELOS LA and BECA CG (1994) Adsorption equilibria between pine bark and several ions in solution. *Eur. Water Pollut. Control* **4** 41-51.

WEBER WJ and MORRIS JC (1963) Kinetics of adsorption on carbon from solution. *J. Sanit. Eng. Div. Am. Soc. Civ. Eng.* **89** 31-60.

WILDJ (1987) Liquid wastes from the metal finishing industry. In: Barnes D, Forster CF and Hrućey SE (eds.) *Surveys in Industrial Wastewater Treatment* Vol. 3. Longman Scientific and Technical, Harlow, Essex, UK, 21-64.

---