Chemical Engineering Journal 161 (2010) 161–166

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Evaluation of Amberlite IRA96 and Dowex 1×8 ion-exchange resins for the removal of Cr(VI) from aqueous solution

Serpil Edebali, Erol Pehlivan*

Department of Chemical Engineering, Selcuk University, Campus, 42079 Konya, Turkey

ARTICLE INFO

Article history:
Received 6 February 2010
Received in revised form 30 April 2010
Accepted 30 April 2010

Keywords:
Hexavalent chromium
Ion-exchange resin
Kinetics
Thermodynamics
Amberlite IRA96
Dowex 1×8

ABSTRACT

The removal of Cr(VI) from aqueous solution by two commercially available resins (Amberlite IRA96 and Dowex 1×8) was investigated. Batch adsorption processes were carried out as a function of time, adsorbent dosage, pH and temperature to evaluate the performance of the resins. The optimum pH for Cr(VI) adsorption was found as 3.0 for these resins. It was found that more than 93% removal was achieved under optimal conditions. The maximum adsorption capacities are 0.46 and 0.54 mmol/g of Amberlite IRA96 and Dowex 1×8 resin for Cr(VI) ion, respectively. The suitability of Freundlich and Langmuir adsorption models were investigated for Cr(VI)-resin equilibrium. A pseudo-second order kinetic model has been proposed to correlate the experimental data. The equilibrium adsorption level for Dowex 1×8 decreased with increasing temperature, while it increased for Amberlite IRA96.

1. Introduction

The pollution of heavy metals in aqueous solutions has become severe with the development of economy. Since heavy metals are major pollutants in marine, ground, industrial and even treated wastewaters, people have paid attention to it which will make us sick such as cancer or even make us to die [1–4].

Heavy metals are important sources of environmental pollution, being some of them very toxic even at low concentrations. The traditional techniques used for metal control are based on chemical precipitation coupled to pre- or post-oxidation/reduction followed by filtration in order to concentrate the species of interest. The main disadvantage of these techniques is the production of solid residues containing toxic compounds whose final disposal is in general land filling (which is the last priority in terms of EU policies). Therefore, the use of other alternative techniques (such as adsorption, ion-exchange, membrane and biological processes) based on physical, chemical and biological mechanisms is advisable in order to protect the environment and at the same time recovering at least available metal [4–6].

Chromium is extensively used in pigments and paints, leather tanning, fungicides, electroplating, cement, steel, ceramic and glass industries [7,8]. The presence of Cr(VI) ion in the wastewater generated from these industries has become a major concern today due to its deleterious effects on health and environment [9–13]. Chromium is unique among regulated toxic elements in the environment in that different species of chromium, specifically chromium (III) and chromium (VI) are regulated in different ways based on their differing toxicities [14]. In general, the Cr(VI) ionic forms are anionic in character, such as: $HCrO_4^-$, CrO_4^{-2}, and $Cr_2O_7^{-2}$ chromate complexes.

The Cr(VI) state is of particular concern because this form is hazardous to health from the fact that the chromium in the aqueous solution can be readily absorbed by marine animals and directly enter the human food chains, thus, presenting a high health risk to consumers. Hexavalent chromium is a strong oxidizing agent which irritates plant and animal tissues and it is carcinogenic and mutagenic and has an adverse potential to modify the DNA transcription process. Therefore, the reduction of amount of this metal ion from such effluents to a permissible limit before discharging them into streams and rivers is very important for human health and environment [10,15].

Cr(VI) ion must be properly treated before it is allowed for direct discharge to natural water streams. During the past several decades, many physicochemical methods have been developed for chromium removal from waste chromium acid solution. These methods include chemical coagulation, adsorption, extraction, ion exchange, application of membrane technology and evaporation recovery. However, these processes have considerable disadvantages including incomplete metal removal, requirements for expensive equipment and monitoring system, high reagent or energy requirements or generation of toxic sludge or other waste products that require disposal [7,8,11–13].

---

* Corresponding author. Tel.: +90 332 2232127; fax: +90 332 2410635.
E-mail address: erolpehlivan@gmail.com (E. Pehlivan).

1385-8947/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.cej.2010.04.059

Table 1
Physicochemical properties of the resins.

Resin	Amberlite IRA96	Dowex 1×8
Type	Anion exchange resins, weakly basic	Anion exchange resins, strongly basic
Matrix	Styrene-divinylbenzene (macroreticular)	Styrene-divinylbenzene (fine mesh)
Functional Group	Tertiary amine	Quaternary amine
Ionic form as shipped	Free base (FB)/moist	Cl^-
Total exchange capacity	1.25 min eq/L	1.2 min eq/L
Moisture holding capacity	57–63%	43–48%
Stability (at pH-range)	0–7	0–14
Uniformity coefficient	1.1 (max.)	1.1 (max.)
Mesh size	16–50 mesh (wet)	50–100

Current technologies in use for metal control are based on liquid–solid phase transfer methods. Although these technologies are quite satisfying in terms of purging the waters from chromium and other heavy metals, they systematically produce solid residues (sludge) containing toxic compounds whose final disposal is generally land filling with related high costs and most importantly results in long-term environmental consequences [14,15]. Sorption, used here as a general term including several mechanisms such as ion-exchange, surface complexation is considered as a common treatment method in many water and wastewater treatment schemes, regulating also the transport of chemical species in aquatic systems [14]. Ion-exchange is one of the most popular methods for the removal of metal ions from aqueous solution [16]. In the last decades, the ion-exchange technology has found widespread application in the removal of heavy metals from industrial wastewaters. The chelating resins are commonly employed as ion-exchange materials, since their ligands can selectively bind to certain metallic ions. Recent studies have shown that ion-exchangers could be used for the selective removal and recovery of Cr(VI) ion [16].

The main objective of this study was to investigate the equilibrium and kinetic parameters of Amberlite IRA 96 and Dowex 1×8 resins. In addition, various parameters such as Cr(VI) ion concentration (5.0–50.0 mmol/L), temperature (293–313 K), and initial pH values (2.0–7.0) were studied to optimize the conditions for effective removal of Cr(VI) ion from aqueous solution.

2. Experiment

2.1. Experimental materials

The resins used in this study were Amberlite IRA96 and Dowex 1×8 which were purchased from Sigma Chem. Co. (Rohm and Haas) and Dow Chem. Co., respectively. Table 1 shows the main physicochemical properties of the resins investigated. All the chemicals used were of analytical grade. Double distilled water was used to prepare all solutions throughout the experiments. Cr(VI) stock solution (from Merck) was prepared by dissolving $K_2Cr_2O_7$ salt in double distilled water. Solutions were stored in plastic sealed beakers.

2.2. Experimental methods

A series of standard Cr(VI) solution were prepared by appropriate dilution of the stock solution. For Cr(VI) ion sorption studies, 40 mg ion-exchange resin was brought in contact with 25 mL of Cr(VI) solution at constant speed using orbital shaker at 25 °C. After filtration, the concentration of Cr(VI) in the filtrate was analyzed spectrophotometrically. Total absorbed Cr(VI) was calculated by taking the difference of initial concentration and total Cr(VI) concentration in the filtrate. The concentrations of Cr(VI) ions in initial and final solutions were determined spectrophotometrically at 540 nm by UV–vis spectrophotometer (Shimadzu UV-1700) using 1,5-diphenyl carbazide as a complexing agent. Diphenylcarbazide gives reaction with Cr(VI) in acid medium and Cr(III)–diphenylcarbazone complex occurs (Eq. (1)) [18,19].

$$2CrO_4{}^{2-} + 3H_4L + 8H^+ \rightarrow Cr(HL)_2{}^+ + Cr^{3+}H_2L + 8H_2O \qquad (1)$$

H_4L: 1,5-Diphenylcarbazide
H_2L: Diphenylcarbazone

Contact time adsorption experiments were conducted at room temperature (25 ± 1 °C) in a well-mixed Pyrex glass vessel with a cover. The effect of the resin dosage for adsorption was studied in the batch vessel by varying the resin from 0.01 to 0.1 g for optimum contact time. The effect of pH on Cr(VI) ion sorption was evaluated by adjusting the initial pH of the initial solution within the range of 2–7. The pH of each solution was adjusted to the desired value with 0.01 M NaOH and HCl. The solutions were agitated in the shaker for 2 h. In addition to these, the effects of concentration and temperature were also investigated in order to determine the optimum conditions for these parameters.

3. Results and discussion

3.1. Effect of contact time

The contact time was varied from 5 to 240 min for the adsorption of Cr(VI) by the ion-exchange resins. The effect of contact time on the adsorption of Cr(VI) is shown in Fig. 1. The adsorption of Cr(VI) increased with increasing contact time and attained an optimum at about 20 min for Dowex 1×8 and 50 min for Amberlite IRA96 resin. High adsorption rates of chromium for the two resins are observed at the onset, and then plateau values are reached.

3.2. Effect of resin amount

The effect of the amount of resin on sorption of Cr(VI) ions was investigated. For this purpose, the resin amounts were taken between 0.01 and 0.1 g. The results in Fig. 2 show that the retention of Cr(VI) ions increased with increasing of resin amount but sorption density decreases and then attained equilibrium.

It is readily understood that the number of available sorption sites increases by increasing the resin amount, therefore results in the increase of removal efficiency for Cr(VI) ion. The decrease in sorption density can be attributed to the fact that some of the sorption sites remain unsaturated during the sorption process; whereas the number of available sorption sites increases by an increase in resin amount and this results in an increase in removal efficiency [20].

3.3. Effect of solution pH

Fig. 3 represents the effect of initial pH on the removal of the Cr(VI) by Amberlite IRA96 and Dowex 1×8 resins. In order to find the optimum pH for maximum removal efficiency, experiments were carried out in the pH range 2–7. Because of precipitation of the

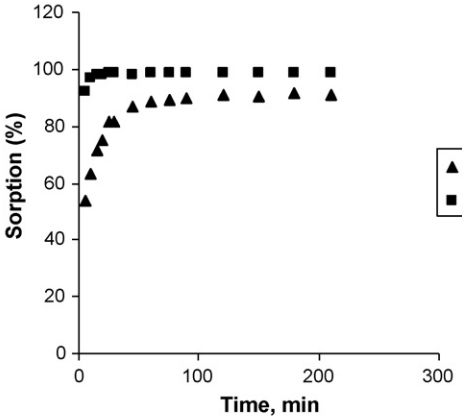

Fig. 1. Effect of contact time on the sorption of Cr(VI) by Amberlite IRA96 and Dowex 1×8 (conditions: initial concentration of Cr(VI), 1×10^{-3} M; amount of resin, 0.04 g; volume of adsorption medium, 25 mL; temperature, 25 ± 1 °C; stirring rate 180 rpm; initial pH, 5.0).

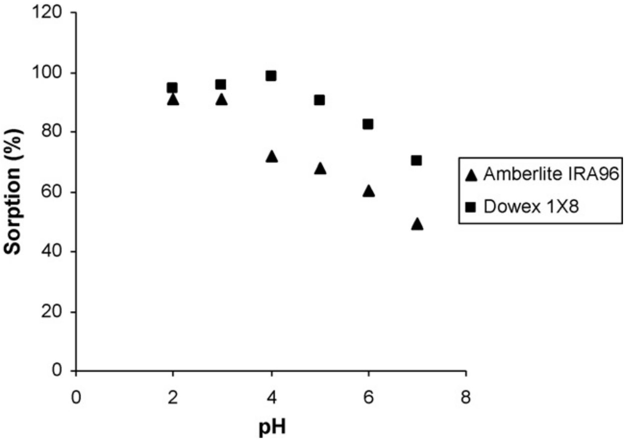

Fig. 3. Effect of pH on the sorption of Cr(VI) by Amberlite IRA96 and Dowex 1×8 (conditions: initial concentration of Cr(VI), 1×10^{-3} M; amount of resin, 0.04 g; volume of adsorption medium, 25 mL; temperature, 25 ± 1 °C; stirring rate 180 rpm; stirring time, 50 min).

Cr(VI) ion, higher pH values were not preferable. The effect of pH on Cr(VI) sorption was determined as batch experiments and the results are given in Fig. 3. The sorption of Cr(VI) with Dowex 1×8 increases marginally with the increase in pH from 2 to 4. Beyond pH 3 for Amberlite IRA96 and beyond pH 4 for Dowex 1×8, there is sharp decrease in Cr(VI) sorption. For both of the resins, the optimum pH was chosen as 3.0.

As pH changes from 1 to 4, the removal of Cr(VI) changes slightly. When pH > 5, the removal of Cr(VI) from the solution decreased sharply as the pH increased. At very low pH values, the surface of the resin would be surrounded by the hydronium ions which enhance the Cr(VI) interaction with binding sites of the resin by greater attractive forces and as the pH increased, however, the overall surface charge on this resin became negative and sorption decreased.

The chromate may be represented in various forms such as H_2CrO_4, $HCrO_4^-$, CrO_4^{2-}, $Cr_2O_7^-$, $Cr_2O_7^{2-}$ in the solution phase as a function of pH and concentration. Only CrO_4^{2-} ions exist in the solution throughout the experimental concentration range when pH > 6.5; in the pH range from 0 to 6.5, $HCrO_4^-$ and $Cr_2O_7^{2-}$ are predominant [17]. It is known from above that the amounts of Cr(VI) ion can be taken by one active site of the resin in acidic condition is double that in alkali condition [19]. The process is reversible and the exchanged OH^- will react with H^+ in acid condition. So the state of equilibrium was destroyed and the forward reaction was enhanced. At alkaline pH values, the sorption trend can likely be ascribed to the effect of competitive binding between CrO_4^{2-} and OH^- for the binding sides on the surface of the resins. At higher pH, an excess of OH^- can compete effectively with CrO_4^{2-} for the bonding sites, resulting in a lower level of Cr(VI) ion uptake. Thus, the range 1–3 and 1–4 is suggested for effective sorption of Cr(VI) with Amberlite IRA96 and Dowex 1×8, respectively [21,22].

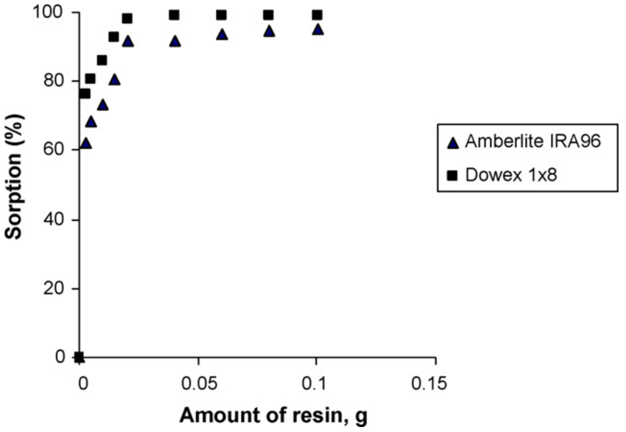

Fig. 2. Effect of resin amount on the sorption of Cr(VI) by Amberlite IRA96 and Dowex 1×8 (conditions: initial concentration of Cr(VI), 1×10^{-3} M; volume of adsorption medium, 25 mL; temperature, 25 ± 1 °C; stirring rate 180 rpm; stirring time, 50 min; initial pH, 5.0).

3.4. *Adsorption isotherms*

The sorption of Cr(VI) ions was carried out at different initial chromium concentrations ranging from 5 to 50 mg/L, at optimum pH with the optimum agitation period (Fig. 4). Sorption isotherms can be used to describe how solutes interact with the resin in the equilibrium. Two kinds of known isotherm equations, Langmuir and Freundlich isotherms, have been applied for this study [19,20]. The sorption data of Cr(VI) ion have been correlated with Langmuir and Freundlich models [Eqs. (2) and (3)]. These isotherms relate metal uptake per unit weight of resin q_e to the equilibrium metal ion concentration in the bulk fluid phase C_e.

Langmuir equation:

$$\frac{C_e}{q_e} = \frac{1}{K_b A_S} + \frac{C_e}{A_S} \tag{2}$$

where, A_s and K_b are coefficients, q_e is the weight sorbed Cr(VI) ion per unit weight of sorbent and C_e is the Cr(VI) ion concentration in bulk solution at equilibrium.
Freundlich equation:

$$q = K_f C_e^n \tag{3}$$

where, n is the Freundlich constant, and K_f is the adsorption coefficient, q is the weight sorbed Cr(VI) ion per unit weight of sorbent and C_e is the equilibrium Cr(VI) concentration in fluid. Taking logs and rearranging the Eq. (4) was obtained.

$$\log q = \log K_f + n \log C_e \tag{4}$$

The linear plots of C_e/q_e versus C_e show that sorption follows the Langmuir adsorption model. The Langmuir model fit well in the pH range between 2.2 and 3.0. The Langmuir equation was more applicable than the Freundlich equation although both described the ion-exchange data adequately. The correlation coefficients are

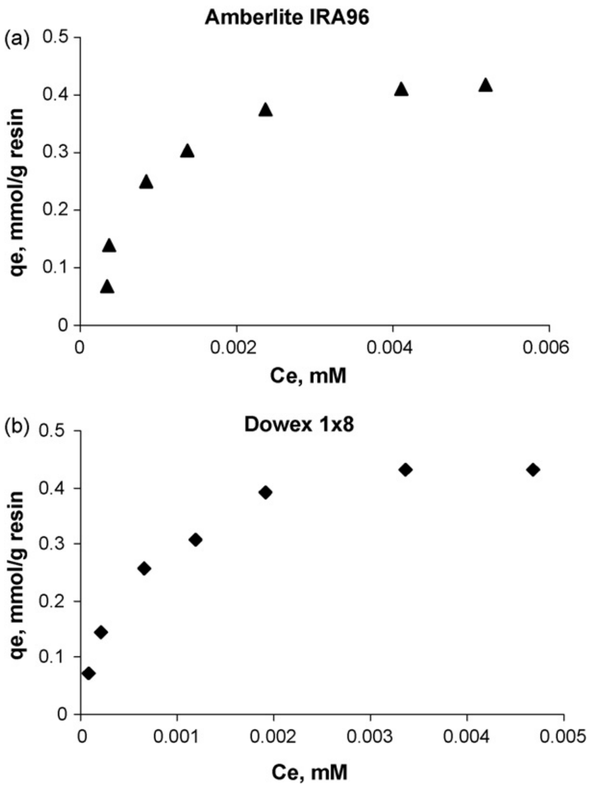

Fig. 4. Sorption isotherm of Cr(VI) on (a) Amberlite IRA96 and (b) Dowex 1×8 (conditions: initial concentration of Cr(VI), 1×10^{-4}–1×10^{-3} M; amount of resin, 0.04 g; volume of adsorption medium, 25 mL; temperature, 25 ± 1 °C; stirring rate 180 rpm; stirring time, 50 min; initial pH, 5.0).

calculated as 0.98 and 0.95 and the maximum adsorption capacities are found as 0.46 and 0.54 mmol per g of Amberlite IRA96 and Dowex 1×8 resins for Cr(VI) ion, respectively from Table 2. Equilibrium isotherm, the relation between the amount exchange (q_e) and the remaining concentration in the aqueous phase (C_e), is important to describe how solutes interact with the resins and so is critical in optimizing the use of them. The amount of Cr(VI) ions adsorbed per unit mass of the Amberlite IRA96 and Dowex 1×8 increased with the initial Cr(VI) ion concentration as expected.

3.5. Effect of temperature on Cr(VI) adsorption

The effects of temperature on the sorption of Cr(VI) by Amberlite IRA96 and Dowex 1×8 are shown in Fig. 5. Temperature of the resin mixture and Cr(VI) solution was ranged from 25 to 45 °C. The equilibrium sorption level for Dowex 1×8 decreased with increasing temperature, while it increased for Amberlite IRA96 and it is sharp from 35 to 45 °C. The sorption of Cr(VI) decreases with increasing temperature. Therefore, a general temperature range is suggested to be 25–35 °C for Dowex 1×8.

Thermodynamically, parameters such as free energy change (ΔG°), enthalpy change (ΔH°) and entropy change (ΔS°) can be calculated using the following Eqs. ((5)–(7)) where K_c is equilibrium constant, C_{Ae} is the equilibrium concentration (mg/L) of the Cr(VI) ion on the resin and C_e is the equilibrium concentration (mg/L) in the solution.

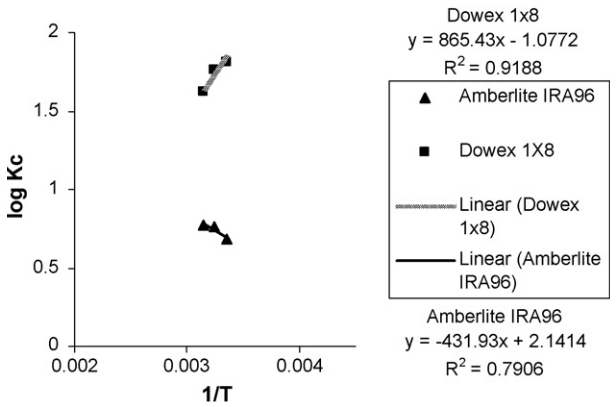

Fig. 5. The equilibrium constants of Cr(VI) on Amberlite IRA96 and Dowex 1×8 as a function of temperature.

$$K_c = \frac{C_{Ae}}{C_e} \tag{5}$$

$$\Delta G^\circ = -RT \ln K_c \tag{6}$$

$$\log K_c = \frac{\Delta S^\circ}{2.303\,R} - \frac{\Delta H^\circ}{2.303\,RT} \tag{7}$$

ΔG°, ΔH° and ΔS° are changes in free energy, enthalpy and entropy, respectively. The linear property of $\log K_c$ against $1/T$ has been researched in some studies on heavy metal adsorption by ion-exchange materials [3]. ΔG°, ΔS° and ΔH° can be calculated from a plot of $\log K_c$ versus $1/T$.

The ion-exchange capacity increases with temperature with the endothermic reactions. It decreases with temperature while the reaction is exothermic [23]. As seen from Table 3, the negative values of ΔG°, indicates exothermic and spontaneous nature of the process and favorable sorption. The positive ΔH° shows that the sorption processes for Amberlite IRA96 is exothermic reaction, while the negative ΔH° for Dowex 1×8 proves it to be an endothermic reaction. The reason why sorption level for Dowex 1×8 decreased increasing temperature while increased for Amberlite IRA96 can be explained by the value of ΔH°.

3.6. Kinetic model theory

In order to investigate the mechanism of sorption and potential rate controlling steps such as mass transport and chemical reaction processes, kinetic models have been used to test experimental data. These kinetic models included the pseudo-first order equation, the pseudo-second order equation.

3.7. The pseudo-first order equation

The pseudo-first order equation of Lagergren is generally expressed as follows [24,25]:

$$\frac{d_{qt}}{dt} = k_1(q_e - q_t) \tag{8}$$

Table 2
Parameters of Langmuir and Freundlich Isotherms for sorption of Cr(VI) on Amberlite IRA96 and Dowex 1×8.

Resin	Freundlich isotherm			Langmuir isotherm		
	K_f	n	Corr. coeff.	K_b	A_s	Corr. coeff.
Amberlite IRA96	4.301	2.399	0.912	1198.118	0.491	0.998
Dowex 1×8	6.059	2.207	0.949	1891.455	0.481	0.998

Table 3
Thermodynamic parameters for the adsorption of Cr(VI) on Amberlite IRA96 and Dowex 1×8.

Resin	ΔH° (J mol^{-1})	ΔS° (J K^{-1} mol^{-1})	ΔG° (J mol^{-1})		
			T = 298 K	T = 308 K	T = 318 K
Amberlite IRA96	8270.56	41.00	−3873.29	−4517.77	−4682.85
Dowex 1×8	−16571.19	−20.63	−10336.22	−10401.44	−9911.78

where q_e and q_t are the sorption capacity at equilibrium and at time t, respectively (mg g^{-1}) and k_1 is the rate constant of pseudo-first order sorption (L min^{-1}). After integration and applying boundary conditions $t = 0$ to $t = t$ and $q_t = 0$ to $q_t = q_t$, the integrated form of Eq. (8) becomes:

$$\log(q_e - q_t) = \log(q_e) - \left(\frac{k_1}{2.303}\right) t \tag{9}$$

The pseudo-second order equation

If the rate of sorption is a second order mechanism, the pseudo-second order chemisorption kinetic rate equation is expressed as [26,27]:

$$\frac{d_{qt}}{d_t} = k(q_e - q_t)^2 \tag{10}$$

where q_e and q_t are the sorption capacity at equilibrium and at time t, respectively (mg g^{-1}) and k is the rate constant of pseudo-second order sorption (g mg^{-1} min^{-1}). For the boundary conditions $t = 0$ to $t = t$ and $q_t = 0$ to $q_t = q_t$, the integrated form of Eq. (10) becomes:

$$\frac{1}{(q_e - q_t)} = \frac{1}{q_e} + kt \tag{11}$$

which is the integrated rate law for a pseudo-second order reaction. q_e is the amount of metal ion sorbed at equilibrium (mg g^{-1}) and k is the equilibrium rate constant of pseudo-second order sorption (g mg min^{-1}). Eq. (11) can be rearranged to obtain a linear form:

$$\frac{t}{q_t} = \frac{1}{kq_e^2} + \left(\frac{1}{q_e}\right) t \tag{12}$$

where h can be regarded as the initial sorption rate as $q_t/t \to 0$, hence:

$$h = kq_e^2 \tag{13}$$

Eq. (13) can be written as:

$$\frac{t}{q_t} = \frac{1}{h} + \left(\frac{1}{q_e}\right) t \tag{14}$$

Eq. (12) does not have the disadvantage of the problem with assigning an effective q_e. If pseudo-second order kinetics is applicable, the plot of t/q_t against t of Eq. (12) should give a linear relationship, from which q_e, k and h can be determined from the slope and intercept of the plot and there is no need to know any parameter beforehand.

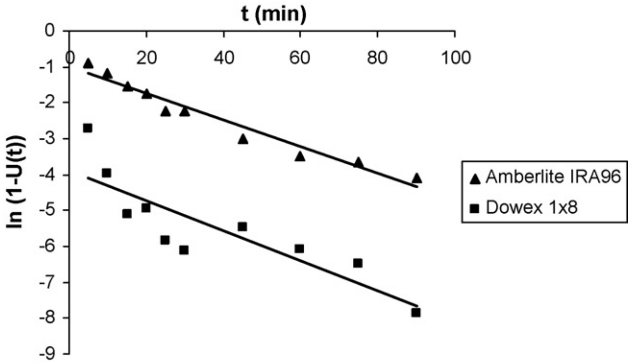

Fig. 6. Pseudo-first order sorption kinetics of Cr(VI) on both Amberlite IRA96 and Dowex 1×8.

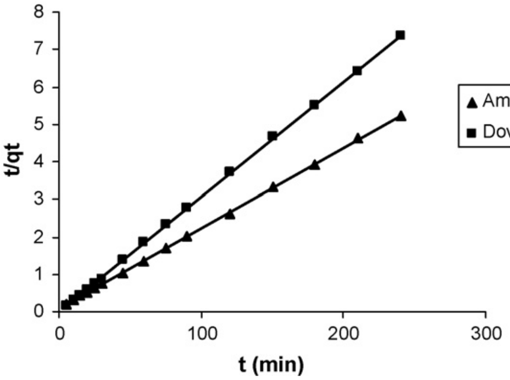

Fig. 7. Pseudo-second order sorption kinetics of Cr(VI) on both Amberlite IRA96 and Dowex 1×8.

Table 4
Kinetic model parameters for Cr(VI) sorption on Amberlite IRA96 and Dowex 1×8.

Models	Parameters	Amberlite IRA96	Dowex 1×8
Pseudo-first order	q_e (mg g^{-1})	19.24	1.06
	R^2	0.957	0.739
	k_1	0.0373	0.0418
Pseudo-second order	q_e (mg g^{-1})	46.73	32.67
	R^2	0.999	0.999
	k_2	5.3×10^{-2}	9.97×10^{-2}
	h	11.6	106.4

Fig. 6 shows plot of q_t against t for the first order equation in terms of Cr(VI) sorption on the resins. The R^2 values were found as 0.957 and 0.739 for Amberlite IRA96 and Dowex 1×8, respectively. Linear plots of t/q_t against t in Fig. 7 shows the applicability of the pseudo-second order equation for the sorption of Cr(VI) with these resins. The correlation coefficients for the linear plots of t/q_t against time from the pseudo-second order rate law are 0.999 for both of them. All parameters related with both pseudo-first order and second order sorption kinetics are given in Table 4. When they are compared, however, the equilibrium sorption capacity for second-order are slightly more reasonable than those of the first-order, so this suggests that this sorption system is not a first-order reaction and that the pseudo-second order model, based on the assumption that the rate-limiting step may be chemical sorption or chemisorption involving valence forces through sharing or exchange of electrons between sorbent and sorbate, provides the best correlation of the data [22,23].

4. Conclusion

The adsorption of Cr(VI) increased with increasing contact time and attained an optimum at about 20 min for Dowex 1×8 and 50 min for Amberlite IRA96 resin. The results from this study show that the retention of Cr(VI) ions increased with increasing of resin amount but sorption density decreases and then attained equilibrium. The optimum pH was chosen as 3.0 for both of the resins. For

Amberlite IRA96, the uptake decreases at higher pH values whereas for Dowex 1×8, the sorption efficiency of Cr(VI) increases with increasing pH of the sorption medium until reaching to the optimum pH for this resin. The ion-exchange capacities of the resins are given as 0.46 and 0.54 mmol Cr(VI)/g resin for Amberlite IRA96 and Dowex 1×8, respectively. This difference in the capacity might be due to the matrix of the resins. The equilibrium sorption level for Dowex 1×8 decreased with increasing temperature, while it increased for Amberlite IRA96 and it is sharp from 35 to 45 °C.

The correlation coefficients or the linear plots of t/q_t against time from the pseudo-second order rate law are greater than 0.990 for all systems. This suggests that this sorption system is not a first-order reaction and that the pseudo-second order model, based on the assumption that the rate-limiting step may be chemical sorption or chemisorption involving valence forces through sharing or exchange of electrons between sorbent and sorbate, provides the best correlation of the data.

Acknowledgement

We would like to thank Selcuk University Research Fund for its financial support for this work (project number: SU-2007/07101031).

References

[1] F.J. Alguacil, A.G. Coedo, T. Dorado, I. Padilla, Recovery of chromium(VI) from hydrochloric acid liquors using the resin Dowex 1×8, J. Chem. Res. (S) (2002) 101–104.
[2] Y. Wu, X. Ma, M. Feng, M. Liu, Behavior of chromium and arsenic on activated carbon, J. Hazard. Mater. 159 (2008) 380–384.
[3] A. Baran, E. Bicak, S.H. Baysal, S. Onal, Comparative studies on the adsorption of Cr(VI) ions on to various sorbents, Bioresour. Technol. 98 (2006) 661–665.
[4] G. Rojas, J. Silva, J.A. Flores, A. Rodriguez, M. Ly, H. Maldonado, Adsorption of chromium onto cross-linked chitosan, Sep. Purif. Technol. 44 (2005) 31–36.
[5] Z. Hu, L. Lei, Y. Li, Y. Ni, Chromium adsorption on high-performance activated carbons from aqueous solution, Sep. Purif. Technol. 31 (2003) 13–18.
[6] A.K. Sengupta, D. Clifford, Important process variables in chromate ion exchange, Environ. Sci. Technol. 20 (1988) 155–160.
[7] S.H. Lin, C.D. Kiang, Chromic acid recovery from waste acid solution by an ion exchange process: equilibrium and column ion exchange modeling, Chem. Eng. J. 92 (2003) 193–199.
[8] S. Kocaoba, G. Akcin, Removal of chromium (III) and cadmium (II) from aqueous solutions, Desalination 180 (2005) 151–156.
[9] R.S. Bai, E. Abraham, Studies on chromium(VI) adsorption–desorption using immobilized fungal biomoss, Bioresour. Technol 87 (2003) 17–26.
[10] E. Korngold, N. Belayev, L. Aronov, Removal of chromates from drinking water by anion exchangers, Sep. Purif. Technol. 33 (2003) 179–187.
[11] L. Khezami, R. Capart, Removal of chromium(VI) from aqueous solution by activated carbons: Kinetic and equilibrium studies, J. Hazard. Mater. B123 (2005) 223–231.
[12] S. Gupta, B.V. Babu, Removal of toxic metal Cr(VI) from aqueous solutions using sawdust as adsorbent: Equilibrium, kinetics and regeneration studies, Chem. Eng. J. 150 (2009) 352–365.
[13] Z. Aksu, F. Gonen, Z. Demircan, Biosorption of chromium(VI) ions by Mowital® B3OH resin immobilized activated sludge in a packed bed: comparison with granular activated carbon, Process. Biochem. 38 (2002) 175–186.
[14] D.E. Kimbrough, Y.C.A.M. Winer, L. Creelman, C. Mabuni, Critical assessment of chromium in the environment, Crit. Rev. Environ. Sci. Technol. 29 (1) (1999) 1–46.
[15] D. Petruzzelli, J.R. Passino, G. Tiravantit, Ion exchange process for chromium removal and recovery from tannery wastes, Ind. Eng. Chem. Res. 34 (1996) 2612–2617.
[16] F.J. Alguacil, M. Alonso, L.J. Lozano, Chromium (III) recovery from waste acid solution by ion exchange processing using Amberlite IR-120 resin: batch and continuous ion exchange modelling, Chemosphere 57 (2004) 789–793.
[17] D. Mohan, C.U. Pittman Jr., Activated carbons and low cost adsorbents for remediation of tri- and hexavalent chromium from water, J. Hazard. Mater. B137 (2006) 762–811.
[18] I. Narin, A. Kars, M. Soylak, A novel solid phase extraction procedure on Amberlite XAD-1180 for speciation of Cr(III), Cr(VI) and total chromium in environmental and pharmaceutical samples, J. Hazard. Mater. 150 (2008) 453–458.
[19] E. Pehlivan, S. Cetin, Sorption of Cr(VI) ions on two Lewatit-anion exchange resins and their quantitative determination using UV–visible spectrophotometer, J. Hazard. Mater. 163 (2009) 448–453.
[20] F. Gode, E. Pehlivan, Removal of chromium from aqueous solutions using Lewatit S 100: the effect of pH, time, metal concentration and temperature, J. Hazard. Mater. B136 (2006) 330–337.
[21] B. Galan, M. Calzada, I. Ortız, Separation and concentration of Cr(VI) from ground waters by anion exchange using Lewatit MP-64: mathematical modelling at acidic pH, Solvent Extr. Ion Exch. 24 (2006) 621–637.
[22] F. Gode, E. Pehlivan, Removal of Cr(VI) from aqueous solution by two Lewatit anion exchange resins, J. Hazard. Mater. B119 (2005) 175–182.
[23] T. Shia, Z. Wanga, Y. Liub, S. Jia, D. Changminga, Removal of hexavalent chromium from aqueous solutions by D301, D314 and D354 anion-exchange resins, J. Hazard. Mater. 161 (2009) 900–906.
[24] Y.S. Ho, G. Mckay, Batch lead(II) removal from aqueous solutıon by peat: equilibrium and kinetics, Trans. IChemE 77 (1999), Part B.
[25] Y.S. Ho, G. McKay, A kinetic study of dye sorption by biosorbent waste product pith resources, Conser. Recyc. 25 (1999) 171–193.
[26] Y.S. Ho, G. McKay, A comparison of chemisorption kinetic models applied to pollutant removal on various sorbents, Trans IChemE 76 (1998) 332–340, Part B.
[27] M.N. Sahmoune, K. Louhab, A. Baukhiar, Kinetic and equilibrium models for the biosorption of Cr(III) on *Streptomyces rimosus*, Res. J. Appl. Sci. 3 (4) (2008) 294–301.