

Scientific paper

Adsorption of Cr(III) from Aqueous Solution using Borax Sludge

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Abstract

Borax sludge is the waste produced by a trommel sieve in the borax production process and is used as an adsorbent for Cr(III) removal. The effects of various parameters, including pH, initial Cr(III) concentration and contact time were investigated for batch adsorption of Cr(III). The experimental results obtained were applied to different adsorption isotherms and kinetic models.

The results indicated that the Temkin isotherm ($R^2 = 0.9749$) was most suitable to explain the adsorption characteristics of borax sludge, and the removal of Cr(III) was achieved by a physisorption process. The overall kinetic data fitted the pseudo-second order rate model ($R^2 = 0.9990$).

According to thermodynamic studies, which were carried out at different temperatures, changes in enthalpy (ΔH) and entropy (ΔS) values for Cr(III) adsorption by borax sludge were determined to be 69.395 kJ/mol and 0.276 kJ/mol K, respectively. The study implied that borax sludge could be used as an alternative adsorbent in the adsorption of Cr(III) from aqueous solutions.

Keywords: Adsorption kinetic, borax sludge, Cr (III), thermodynamic

1. Introduction

The main types of pollution, according to environmental factors, are classified as water pollution, air pollution, soil pollution, radioactive contamination and microbiological contamination. Water pollution, which can be caused by sewage, solid wastes, radiation, toxic chemicals and pesticides etc., is a natural imbalance in the water environment and one of the major environmental hazards of the entire world. Heavy metal contamination is a permanent toxic chemical pollution and has adverse effects for human health and the environment.

Being a water-contaminating metal, chromium is ubiquitous in nature, existing as approximately 0.1 mg/m³ in the air and at 1 mg/L in unpolluted water.⁴ Therefore, exposure to chromium in high concentrations has a negative effect on fertility, the respiratory system and can also cause cancer.^{5–7} Removing chromium ions from aqueous mediums is significant for both human health and the en-

vironment. Thus, many researchers have applied various methods, including ion exchange, osmosis, foam flotation, electrolysis and surface adsorption to reduce chromium concentration under the Minimal National Standards (MINAS) upper limit for industrial wastewater, which is 0.1 mg/L. 8,9 Adsorption is a process for removal of heavy metals that receives attention due to its ease, and its economic and efficiency advantages.

In published literature, various adsorbents have been used for the removal of the two main types of chromium ions: Cr(VI) and Cr(III), by changing adsorption parameters such as chromium concentration, adsorbent dose, pH, temperature and agitation time. Various research has been reported for chromium removal from aqueous medium using chemical, biological and industrial waste materials as adsorbents. During biosorption processes, the performances of different biological adsorbents such as chitosan, thuja oriantalis, activated rice husk carbon, neem leaves, activated red mud, hazelnut shell activated carbon, agave

lechuguilla biomass and soya cake have been investigated for chromium adsorption. ^{10–17} In many adsorption processes, layered double hydroxide, Turkish brown coals, ozonised activated carbon, acrylate-based magnetic beads and bentonite clay have been studied as chemical adsorbents. ^{18–23} In addition to these studies, some industrial wastes such as fly ash and saw dust, and also Indian Rosewood timber have been preferred because of their economical usage. ^{24,25}

The evaluation of borax sludge is highly important, due to the emerging amount of boron waste in Turkey, which is 600000 tons per year. ^{26,27} It is envisaged that this amount will increase in future years depending on the consumption of boron sources and use of waste boron in different production processes. Storage problems and storage costs will be reduced and the polluting elements will be minimized by using boron wastes in industrial applications such as adsorption techniques.

The use of waste materials as low-cost adsorbents is attractive due to their contribution to the reduction of costs for waste disposal. Even though there have been a variety of adsorption studies performed on boron waste, chromium adsorption using boron waste has not yet been investigated.²⁸ In published literature, boron waste has been used as an adsorbent in adsorption studies for dye, cadmium (II) and zinc (II).^{29,30}

The purpose of this study is to investigate the possibility of using borax sludge as a low cost adsorbent for chromium adsorption. The adsorption performance of borax sludge was studied by varying parameters such as the contact time and the initial Cr(III) concentration. In this study, the adsorption of Cr(III) from aqueous solutions under different kinetic and equilibrium conditions was investigated in detail.

2. Experimental

2. 1. Raw Material Preparation

Borax sludge, which was used as an adsorbent for removing Cr(III) ions from aqueous medium, was supplied by the Eti Mine Bandirma Boron Works (Balikesir, Turkey). Before using the sludge in experimental studies, the adsorbent was dried in an incubator (Ecocell 111, Germany) at 105 °C for 2 hours to eliminate its moisture content. The dried adsorbent was ground with an agate mortar and sieved with a vibrating sieve-shaker (Fritsch, Germany) to produce a particle size below 90 µm. Following this preparation step, identification studies were carried out using a PANalytical Xpert Pro (PANalytical B.V., The Netherlands) X-ray diffractometer (XRD) with a Cu-Kα tube and parameters of 45 kV and 40 mA. The composition of adsorbents was determined by a PANalytical Minipal X-ray fluorescence (XRF) spectrometer (PANalytical B.V., The Netherlands). The BET surface areas of adsorbents were measured on a Micromeritics ASAP 2020 instrument using N_2 adsorption after degassing the adsorbent at 300 °C for 8 hours.

A stock solution of Cr (III) was prepared by dilution of a standard chromium solution (from Cr(NO₃)₃ – supplied by Merck KGaA, Darmstadt, Germany – with double distilled water.

2. 2. Adsorption Experiments

With the aim of determining the effect of pH on the removal of Cr(III), batch adsorption studies were carried out by varying the pH of the solution from 3 to 11; the contact time and initial Cr(III) concentration were set to 180 minutes and 40 mg/L, respectively. The pH of the solutions was adjusted by using 1 M NH_3 and HCl as required.

For the isotherm studies and kinetic investigations, 0.05 g of borax sludge was added to 50 mL of Cr(III) solution with varying initial Cr(III) concentrations (10–40 mg/L), and mixing was carried out for different contact times (15–180 min) at a speed of 200 rpm. The adsorption temperature was set to 20 °C. At the end of each adsorption period, the adsorbents were filtered through filter paper (Blue ribbon, Chmlab) and the residual Cr(III) concentration was analyzed by an Inductively Coupled Plasma–Optical Emission Spectrometer (ICP-OES) (Optima DV 2100, Perkin Elmer, USA). The amount of adsorbed Cr(III) after a pre-determined contact time was calculated by using the expression in Eq. (1):

$$q = \frac{C_i - C_f}{m} xV \tag{1}$$

where q is the removal capacity of the adsorbent at equilibrium (mg/g), V is the volume of the suspension (mL), m is the weight of adsorbents (in gms), C_i and C_f are the initial and final concentrations of Cr (III) (in mg/L), respectively.³¹

For thermodynamic studies, experiments were carried out at various adsorption temperatures (20 $^{\circ}$ C, 30 $^{\circ}$ C, 40 $^{\circ}$ C and 50 $^{\circ}$ C) and equilibrium adsorption parameters.

2. 3. Isothermal Analysis and Kinetic Studies

The equilibrium data were fitted to the adsorption isotherms models of Langmuir, Freundlich, Temkin, Dubinin-Radushkevich and Harkins-Jura – which give information about the adsorption process and explain the equilibrium relationship between the amount of adsorbed sample uptake and the concentration at a constant temperature – were applied to find out the effects of different initial concentrations and related times for the use of borax sludge. 32–34

The Langmuir isotherm, which neglects lateral interactions, was fitted to obtain the experimental quantities (Eq. (2)):

$$q_e = \frac{q_{\text{max}} K_L C_e}{1 + K_L C_e} xV \tag{2}$$

where q_e (mg/g) is the amount of Cr(III) adsorbed per unit mass of adsorbent, q_{max} is the maximum adsorption capacity of adsorbent (mg/g), C_e is the concentration of Cr(III) in suspension at equilibrium (mg/L) and K_L is the Langmuir constant related to the affinity of the binding sites. 24,34 When a linear plot of $1/q_e$ versus $1/C_e$ is drawn, the values of K_L and q_{max} can be obtained from the slope and the intercept of the plot, respectively (Table 1). In Langmuir isotherms, the separation factor, R_L , is used to indicate the essential features of the isotherm. When R_L is between 0 and 1, it indicates that adsorption is favorable Eq. (3):

$$R_L = \frac{1}{1 + K_L Ci} \tag{3}$$

The Freundlich isotherm is expressed by Eq. (4):

$$q_e = K_F C_e^{1/n} \tag{4}$$

where K_F is an approximate indicator of adsorption capacity and n is a constant for the intensity of adsorption. The values of K_F and n can be determined from the plot of $\ln q_e$ versus $\ln C_e$ which are obtained by linear approximations of Eq. (4). 31,36

The Temkin isotherm takes into consideration the influences of some indirect interactions between adsorbent and adsorbate. The model assumes that the relationship between the decrease in adsorption heat and temperature is linear rather than logarithmic, and is affected by the surface coverage. The Temkin isotherm model is represented by Eq. (5) and Eq. (6):

$$q_e = B_T \ln A_T + B_T \ln C_e \tag{5}$$

$$B_T = \frac{RT}{b_r} \tag{6}$$

where B_T is the Temkin constant related to the heat of adsorption (kJ/mol), A_T is the equilibrium binding constant, R is the gas constant (8.314 J/mol K), T is the temperature (K). The values for A_T , B_T and b_t are calculated from the plot of q_e versus $\ln C_e$.

The equilibrium data were also applied to the Dubinin-Radushkevich isotherm model, which is claimed to be an empirical adaptation of the Polanyi adsorption potential theory. This isotherm model is used to estimate the porous apparent free energy and the characteristics of adsorption (physical or chemical). The Dubinin-Radushkevich isotherm model is represented by Eq. (7) and Eq. (8):

$$q_{e} = (q_{m}) \exp(-B\varepsilon^{2}) \tag{7}$$

$$\varepsilon = RT \ln(1 + \frac{1}{C_e}) \tag{8}$$

where B is the Dubinin–Radushkevich isotherm constant (mol²/K/J²), which gives an idea about the mean free ener-

gy E (kJ/mol) of adsorption per molecule of adsorbate during transfer of the solid to the surface from the solution (Eq. (9):

$$E = \frac{1}{\sqrt{2B}} \tag{9}$$

The values of B, q_m and E can be calculated from the slope and intercept of the plot between $\ln q_e$ versus ε^2 .

The Harkins-Jura isotherm model explains the possibility of multilayer adsorption with the existence of heterogeneous pore distribution. The Harkins-Jura isotherm model can be expressed by Eq. (10). The adsorption constants of A_H and B_H are calculated from the plot of $1/q_e^2$ versus $\log C_e^{.37-39}$

$$q_e = \sqrt{\frac{A_H}{B_H + \log C_e}} \tag{10}$$

The Lagergren pseudo-first order kinetic model, pseudo-second order kinetic model, intraparticle diffusion, and Natarajan and Khalaf models were fitted to experimental data for investigation of the kinetic parameters and mechanism of Cr(III) adsorption. The Lagergren pseudo-first order kinetic model can be expressed by Eq. (11):

$$\frac{dq_t}{dt} = k_1(q_e - q_t) \tag{11}$$

where k_1 is the pseudo-first order rate constant (min⁻¹), q_t and q_e are the amounts of absorbed Cr(III) per unit mass of adsorbent at time t and equilibrium time (mg/g), respectively.

The pseudo-second order kinetic model is given by Eq. (12):

$$\frac{dq_t}{dt} = k_2 (q_e - q_t)^2 \tag{12}$$

and k_2 is the pseudo-second order rate constant (g/mg min).

The intraparticle diffusion kinetic model, which gives information about the adsorption mechanism is described by Eq. (13):

$$dq_t = k_{id}t^{0.5} + A \tag{13}$$

In Eq. (13), q_t is the amount of absorbed Cr(III) per unit mass of adsorbent at time t (mg/g), t is the contact time (min), k_{id} is the intraparticle diffusion rate constant (mg/g min^{1/2}) and A is a constant.

Natarajan and Khalaf explained the relationship between the initial concentration (C_o) and the concentration at time t (C_t) . The linear approximations for the equations the Natarajan and Khalaf first order model is given by Eq. (14):

$$\log \frac{C_o}{C_t} = \frac{k_n}{2.303}t\tag{14}$$

The appropriate kinetic model which explains kinetics and mechanisms of Cr(III) adsorption can be determined by drawing linear plots for each kinetic model and calculation the correlation coefficient for R² for each model.

2. 4. Thermodynamic Studies

Different adsorption temperatures (20 °C, 30 °C, 40 °C and 50 °C) were used to predict thermodynamic parameters such as the Gibbs free energy (ΔG), enthalpy (ΔH) and entropy (ΔS) by using the following equations:

$$\Delta G = -RT \ln K_d \tag{15}$$

$$\Delta G = \Delta H - T \Delta S \tag{16}$$

$$InK_d = -\frac{\Delta H}{RT} + \frac{\Delta S}{R} \tag{17}$$

In the equations, K_d is the distribution coefficient of adsorbent (C_e/q_e), R is the gas constant (8.314 J/mol K), T is the adsorption temperature (K). From the plot between $\ln Kd$ and 1/T, ΔH and ΔS can then be calculated. ^{40–41}

3. Results and Discussion

3. 1. Characterization Results of Adsorbent

The XRD pattern for borax sludge is given in Fig. 1. According to the XRD results, borax sludge was identified as a mixture of dolomite (pdf. no: 00-005-0622; Ca- $Mg(CO_3)_2$) and tincalconite (pdf. no: 00-008-0049; $Na_2B_4O_7$ $5H_2O$) phases.

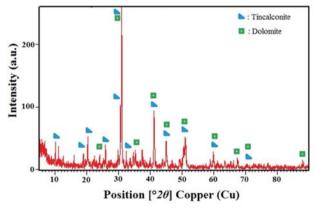


Fig. 1: XRD pattern of borax sludge

According to the XRF results, the composition of borax sludge was CaO 57.3%, MgO 22%, SiO $_2$ 20% and K $_2$ O 0.95%. Although having boron compounds in its composition, XRF showed an inability to measure the boron amount because of its low molecular weight.

The BET surface area for the borax sludge was determined to be 5.54 m²/g. From the characterization re-

sults of the adsorbents, it can be seen that borax sludge has a similar chemical composition and features to pure dolomite.⁴²

3. 2. Adsorption Results

The adsorbed Cr(III) percentage is presented in Fig. 2 for various pH values. The pH of the original solution was 2, and the removal efficiency of Cr(III) showed an increase as the pH increased to 9. The increase in the adsorbed amount of Cr(III) in an alkaline environment indicated that pH values had a major effect on the adsorption mechanism.

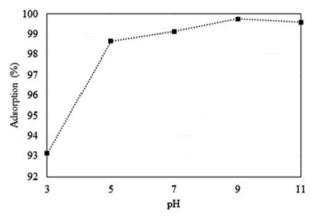


Fig. 2: Adsorption of Cr(III) produced by various pH values

The increase in removal percentage at a higher pH value can be explained by the precipitation of Cr(OH)₃ on the borax sludge by surface adsorption. The probable removal mechanism of Cr(III) by borax sludge can be explained in three steps: (1) the dissolution of dolomite and tincalconite in the borax sludge and the formation of Ca²⁺, Mg²⁺ and Na⁺ cations; (2) the formation of Cr(OH)₃ precipitate; (3) the cations on the adsorbent (Ca²⁺, Mg²⁺ and Na⁺) are exchanged with Cr³⁺ According to the adsorption results, the steps of waste dissolution and Cr(OH)₃ precipitation progress successfully in the experiments by increasing the pH values. This indicates that the adsorption mechanism proceeds well in an alkaline environment.

The results of the adsorption experiments are given in Fig. 3 by the plot of q values against t. The removal of Cr(III) increased with increasing time. In the adsorption experiments, there was a strong increase in the amount of adsorbed Cr(III) ions between 15 and 60 minutes. Maximum adsorption amounts were obtained at 120 minutes and only minor changes were observed for longer contact times. Hence, 180 minutes was assumed to be the required contact time for the equilibrium state. The changes in q values for the experiments on borax sludge adsorption can be explained by the minor differences in chemical composition of the borax sludge. The highest q value was found to be 15.986 mg/g.

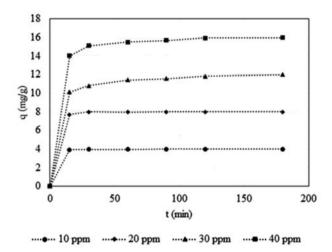


Fig. 3: Removal of Cr(III) depending on contact time

3. 3. Results of Isothermal Analyses and Kinetics

Table 1. Isotherm parameters for the adsorption of borax waste

Isoterms	Plot	Parameters	Results
Langmuir	1/q _e vs 1/C _e	$q_{\rm m}$	24.096
	c c	K_L	41.5
		R_L	0.0006
		$R^{\overline{2}}$	0.8320
Freundlich	log q _e vs log C _e	K _F	41.459
		n	2.545
		\mathbb{R}^2	0.7876
Temkin	q _e vs lnC _e	B _T	3.670
		$A_{\rm T}$	784.631
		\mathbf{b}_{t}	0.675
		\mathbb{R}^2	0.9749
Dubinin-	$lnq_e vs \epsilon^2$	$q_{\rm m}$	14.756
Radushkevic	eh	B	9.10^{-9}
		E	7.450
		\mathbb{R}^2	0.8488
Harkins-Jura	$1/q_e^2 \text{ vs logC}_e$	A _H	30.300
		B_{H}	1.039
		R^2	0.5014

Table 2. Kinetic results for the adsorption process

Kinetic Model	C ₀ (p)	pm) 10	20	30	40
Lagergren Pseudo first order	q _e	0.1002	0.1814	15.7797	2.0305
	ĸ	0.0405	0.0244	0.0302	0.0368
	\mathbb{R}^2	0.8383	0.5940	0.9848	0.9506
Pseudo-second order	q_e	4.0012	8.0192	11.7239	16.0000
	K	4.0700	2.1353	0.0107	0.2902
	\mathbb{R}^2	0.9990	0.9998	0.8606	0.9903
Intraparticle diffusion	K _{id}	0.0054	0.0322	1.0218	0.0961
	A	3.9317	7.6236	0.0328	14.7630
	\mathbb{R}^2	0.8839	0.7958	0.8232	0.8877
Natarajan and Khalaf	K _n	0.0387	0.0514	0.0926	0.0454
	R^2	0.8216	0.7816	0.9563	0.9398

The adsorption results for the equilibrium state (contact time of 180 minutes and a pH value of 9) for each initial concentration were applied to various isothermal models. The results for the isothermal analysis are given in Table 1. Comparing the isotherm results, the best fitting adsorption isotherms – considering the correlation coefficient obtained for the isotherms -were in the following order: Temkin > Dubinin-Radushkevich > Langmuir > Freundlich > Harkins-Jura isotherms. The highest correlation coefficient was obtained for the Temkin isotherm model ($R^2 = 0.9749$), which shows that the Temkin isotherm was the most suitable model to explain the adsorption of Cr(III) onto borax sludge. According to the Temkin isotherm model, when the adsorbed Cr(III) amount on the sludge surface increased, the heat of adsorption decreased linearly. The Temkin isotherm assumes a low b_{τ} (0.675) value pointing to weak interactions between the adsorbent and adsorbate, which indicates the adsorption mechanism is physical.^{37–39}

The adsorption kinetics were investigated to examine the controlling mechanism for this adsorption process. The results of the applied kinetic models are given in Table 2. The highest correlations factors were determined in the pseudo-second order kinetic model. According to the pseudo-second order kinetic equation, this adsorption is mainly controlled by the surface. K and q_a values were

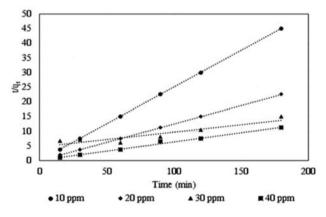


Fig. 4: Pseudo – second order kinetic plots

calculated from the relationship of t/qt versus time, and are presented in Fig. 4. K constants were found to be in the range from 4.0700 to 0.2902 for borax sludge. The q_e values obtained for borax sludge (16.000–4.001 mg/g) were compatible with previous studies which calculated the q_{max} value of dolomite for Cr(III) removal as 10.0 mg/g (20 °C).

3. 4. Results of the Thermodynamic Studies

The thermodynamic studies were conducted on the equilibrium state (contact time of 180 minutes and a pH value of 9). The results of thermodynamic experiments for Cr(III) adsorption are presented in the plot of $\ln K_d$ versus I/T (Fig. 5) and the thermodynamic parameters calculated for the adsorption process are given in Table 3.

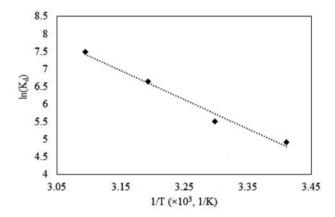


Fig. 5: Plot of $\ln K_d$ versus 1/T for Cr(III) adsorption by borax sludge

Table 3. Thermodynamic parameters for the adsorption process

T(K)	ΔH (kJ/mol)	ΔS(kJ/molK)	ΔG (kJ/mol)
293	69.395	0.276	-11.619
303			-14.384
313			-17.149
323			-19.914

According to Table 3, the Gibbs free energy change (ΔG) showed similarity to the experimental range of temperatures. The negative values of ΔG at different temperatures showed that adsorption of Cr(III) onto borax sludge is spontaneous, and the degree of spontaneity increases with increasing adsorption temperature. The ΔG values also confirmed that the adsorption of Cr(III) onto borax sludge is a physical process with the physical adsorption values ranging from -20 to 0 kJ/mol (while values from -80 to -400 kJ/mol describes chemical absorption). Based on equations (15) to (17), the enthalpy (ΔH) value was determined to be 69.395 kJ/mol for borax sludge, indicating the endothermic behavior of the adsorption process.

The entropy (ΔS) value of borax sludge was found to be 0.276 kJ/mol K. The positive value of ΔS suggests the increased randomness at the solid/solution interface during the adsorption of Cr(III) onto borax sludge.^{37–39}

4. Conclusion

In this study borax sludge was used as an adsorbent for the removal of Cr(III) from waste water. To investigate the potential use of borax sludge, varying parameters, such as the contact time, the initial Cr(III) concentration, the pH and the adsorption temperature were used. Various adsorption isotherms were used to describe the observed adsorption phenomena. The Lagergren pseudo-first order kinetic model, pseudo-second order kinetic model, intraparticle diffusion and Natarajan and Khalaf models were used for investigation of the kinetic parameters and mechanism of the Cr(III) adsorption. Gibbs free energy (ΔG), enthalpy (ΔH) and entropy (ΔS) values were calculated by using the kinetic data.

This study showed that the borax sludge has been evaluated as a possible adsorbent for the removal of Cr(III) from waste water. An initial pH of 9 – where pH has a major effect on the adsorption mechanism – was found to be optimum for maximizing the Cr(III) adsorption. The adsorption is best described by the Temkin isotherm model while the adsorption mechanisms were best explained by the pseudo-second order kinetic model. ΔH and ΔS values were calculated to be 69.40 kJ/mol and 0.276 kJ/mol K for borax sludge, respectively. The negative ΔG values obtained from thermodynamic calculations confirm the feasibility of adsorption. In conclusion, borax sludge, which is readily available in Turkey, can be used as a potential adsorbent for the removal of Cr(III) from waste water.

5. References

- 1. M. W. Holdgate, Cambridge University Press, 1979.
- S. Kolemen, N. B. Acarali, N. Tugrul, E. M. Derun and S. Piskin, *Water, Air, Soil Pollut.*, 2013, 224, 1367. https://doi.org/10.1007/s11270-012-1367-2
- C. Bolognesi, E. Landini, P. Roggieri, R. Fabbri and A. Viarengo, *Environ. Mol. Mutagen.*, 1999, 33, 287–292.
 https://doi.org/10.1002/(SICI)1098-2280(1999)33:4<287:: AID-EM5>3.0.CO;2-G
- Kahvecioglu, G. Kartal, A. Guven and S. Timur, *Metallurgy*, 2004, 136, 47–53.
- A. H. Smith and C. M. Steinmaus, *Annu. Rev. Publ. Health*, 2009, 29, 107–122.
 - https://doi.org/10.1146/annurev.publhealth.031308.100143
- A. Elbetieha and M.H. Al-Hamood, *Toxicology*, **1997**, *116*, 39–47. https://doi.org/10.1016/S0300-483X(96)03516-0
 W. Mertz, *J. Nutr.*, **1993**, *123*, 626–633.

- 8. S. Rengaraj, K. H. Yeon and S. H. Moon, *J. Hazard. Mater.*, **2001**, 87, 273–287. https://doi.org/10.1016/S0304-3894(01)00291-6
- 9. S. Debnath and U. C. Ghosh, *J. Chem. Thermodyn.*, **2008**, 40, 67–77. https://doi.org/10.1016/j.jct.2007.05.014
- S. P. Ramnani and S. Sabharwal, *React. Funct. Polym.*, **2006**, 66, 902–909.
 - https://doi.org/10.1016/j.reactfunctpolym.2005.11.017
- E. Oguz, Colloids Surf., A, 2005, 252, 121–128. https://doi.org/10.1016/j.colsurfa.2004.10.004
- N. R. Bishnoi, M. Bajaj, N. Sharma and A. Gupta, *Bioresour. Technol.*, 2004, 91, 305–307.
 https://doi.org/10.1016/S0960-8524(03)00204-9
- B. V. Babu and S. Gupta, Adsorption, 2008, 14, 85–92. https://doi.org/10.1007/s10450-007-9057-x
- J. Pradhan, S. N. Das and R. S. Thakur, *J. Colloid Interface Sci.*, **1999**, 217, 137–141. https://doi.org/10.1006/jcis.1999.6288
- 15. M. Kobya, Adsorpt. Sci. Technol., 2004, 22, 52-64.
- J. R. Gonzalez, J. R. P. Videa, E. Rodrigueza, S. L. Ramirez and J. L. G. Torresdey, *J. Chem. Thermodyn.*, 2005, 37, 343–347. https://doi.org/10.1016/j.jct.2004.09.013
- 17. N. Daneshvar, D. Salari and S. Aber, *J. Hazard. Mater.*, **2002**, *B94*, 49–61.
 - https://doi.org/10.1016/S0304-3894(02)00054-7
- R. L. Goswamee, P. Sengupta, K. G. Bhattacharyya and D. K. Dutta, *Appl Clay Sci.*, **1998**, *13*, 21–34. https://doi.org/10.1016/S0169-1317(98)00010-6
- 19. N. Das, J. Konar, M. K. Mohanta and S. C. Srivastava, *J. Colloid Interface Sci.*, **2004**, 270, 1–8. https://doi.org/10.1016/S0021-9797(03)00400-4
- F. Gode and E. Pehlivan, Fuel Process. Technol., 2005, 86, 875–884. https://doi.org/10.1016/j.fuproc.2004.10.006
- J. R. Utrilla and M. S. Polo, Water Res., 2003, 37, 3335–3340. https://doi.org/10.1016/S0043-1354(03)00177-5
- 22. G. Bayramoglu and M. Y. Arica, *Chem. Eng. J.*, **2008**, *139*, 20–28. https://doi.org/10.1016/j.cej.2007.07.068
- 23. S. S. Tahir and R. Naseem, *Sep. Purif. Technol.*, **2007**, *53*, 312–321. https://doi.org/10.1016/j.seppur.2006.08.008
- A. K. Bhattacharya, T. K. Naiya, S.N. Mandal, S. K. Das, *Chem. Eng. J.*, 2008, 137, 529–541.

- V. K. Garg, R. Gupta, R. Kumar and R. K. Gupta, *Bioresour. Technol.*, 2004, 92, 79–81.
 https://doi.org/10.1016/j.biortech.2003.07.004
- F. Oruc, E. Sabah and Z. M. Erkan, 2nd International Boron Symposium, 2004.
- 27. Y. Erdogan and T. A. Baydır, *Journal of Science and Technology of Dumlupinar University*, **2013**, *31*, 39–46.
- 28. A. Bhatnagara and M. Sillanpaa *Chem. Eng. J.*, **2010**, *157*, 277–296. https://doi.org/10.1016/j.cej.2010.01.007
- 29. A. Olgun and N. Atar, *J. Hazard. Mater.*, **2009**, *161*, 148–156. https://doi.org/10.1016/j.jhazmat.2008.03.064
- N. Atar, A. Olgun and S. Wang, *Chem. Eng. J.*, **2012**, *192*, 1–7. https://doi.org/10.1016/j.cej.2012.03.067
- G. Qiu, Q. Xie, H. Liu, T. Chen, J. Xie and H. Li, *Appl Clay Sci.*, 2015, 118, 107–115. https://doi.org/10.1016/j.clay.2015.09.008
- 32. R. I. Masel, first ed. John Wiley and Sons, 1996.
- 33. A. Dabrowski, *Adv. Colloid Interface Sci.*, **2001**, *93*, 135–224. https://doi.org/10.1016/S0001-8686(00)00082-8
- 34. A. V. Tvardovskiy, first ed. Elsevier, 2007.
- A. Ghaemi, M. Torab-Mostaedi and M.Ghannadi-Maragheh, *J. Hazard. Mater.*, 2011, 190, 916–921. https://doi.org/10.1016/j.jhazmat.2011.04.006
- V. S. Munagapati, D. Kim, Ecotoxicol. Environ. Saf., 2017, 141, 226–234.
- R. Slimani, I. Ouahabi, A. Elmchaouri, B. Cagnon, S. Antri,
 S. Lazar, *Chemical Data Collections*, 2017, 9, 184–196.
- A. B. Albadarin, C. Mangwand, A. H. Al-Muhtaseb, G. M. Walker, S. J. Allen and M. N. M. Ahmad, *Chem. Eng. J.*, 2012, *179*, 193–202. https://doi.org/10.1016/j.cej.2011.10.080
- V. Srihari and A. Das, *Desalination*, 2008, 225, 220–234. https://doi.org/10.1016/j.desal.2007.07.008
- 40. M. S. Yilmaz, O. D. Ozdemir, S. Kasap and S. Pişkin, *Res. Chem. Intermed.*, **2015**, *41*, 1499–1515.
- 41. M. S. Yilmaz, O. D. Ozdemir, and S. Pişkin, *Res. Chem. Intermed.*, **2015**, *41*, 199–211.
- 42. I. Y. Elbeyli, *Turkish Journal of Engineering and Environmental Sciences*, **2004**, 28, 281–287.

Povzetek

Adsorpcija Cr(III) iz vodne raztopine je bila proučevana v odpadni boraksovi gošči. V šaržnem procesu so bili raziskani vplivi pH-ja, začetne koncentracije Cr(III) in kontaktnega časa. Eksperimentalni rezultati so bili obdelani z različnimi adsorpcijskimi izotermami in kinetičnimi modeli. Adsorpcijske karakteristike se da najbolje razložiti s Temkinovo izotermo ($R^2 = 0.9749$); odstranjevanje Cr(III) poteka s fizisorpcijo. Kinetični podatki pa se najbolje prilegajo hitrostnemu modelu pseudo-drugega reda ($R^2 = 0.9990$). Termodinamika procesa je bila proučevana pri različnih temperaturah. Spremembi vrednosti entalpije (ΔH) in entropije (ΔS) sta 69,40 kJ/mol in 0,276 kJ/mol K. Rezultati kažejo, da se lahko odpadna boraksova gošča uporablja kot alternativni adsorbent za odstranjevanje Cr(III) iz vodne raztopine.