



Trends in
**Applied Sciences
Research**

ISSN 1819-3579



Academic
Journals Inc.

www.academicjournals.com

Kinetic Study of Adsorption of Chromium and Lead Ions on Bentonite Clay Using Novel Internal Series Model

Saad A. Al-Jlil

National Center for Membrane Technology, King Abdulaziz City for Science and Technology, P.O. Box 6086, Riyadh, Kingdom of Saudi Arabia

ABSTRACT

The aim of this study was to determine the use of Bentonite clay from Saudi Arabia for the adsorption of chromium and lead ions from wastewater. The maximum adsorption capacity of Bentonite clay was 13.79 mg g^{-1} for chromium ions and 51.19 mg g^{-1} for lead ions. The Saad model was used to fit the isotherm experimental data and it described the experimental data very well. Also, increasing the agitation speed increased the adsorption rate of chromium (Cr) and lead (Pb) on Bentonite clay. The kinetics of chromium and lead ions on Bentonite clay were determined by a novel diffusion model to calculate the time adsorption constants in a batch adsorber. This model is called as Saad Two Series Internal Diffusion Resistances Model (STSIDRM). In conclusion, the internal mass diffusion proved to be a major rate-controlling step for maximum removal and adsorption of chromium and lead ions from wastewater.

Key words: Bentonite clay, chromium, lead, agitation speed, internal diffusion resistance, two series model, adsorption capacity

INTRODUCTION

Among the various heavy metal pollutants, the presence of chromium and lead in wastewater is harmful to soil and water environments. Generally, removal of heavy metals from wastewater is carried through adsorption process by activated carbon (Quek *et al.*, 1998) and is considered relatively expensive when compared to other adsorbents. Currently, clay can be used an alternative adsorbent as a low cost adsorbent. Previously, different types of clay were used for the adsorption of heavy metals from wastewater (Potgieter *et al.*, 2006; Unuabonah *et al.*, 2007a; Singh *et al.*, 2001; Unuabonah *et al.*, 2007b; Diaz *et al.*, 2007; Al-Jlil and Alsewailem, 2009). A review of literature showed that no research is done on Bentonite clay (from Saudi Arabia) as an adsorbent to adsorb lead and chromium ions from wastewater.

The saturation capacity of lead ions on clay from South Africa was 62.1 mg g^{-1} in a batch adsorber which increased with an increase in the pH of the solution (Potgieter *et al.*, 2006). The lead ions adsorption on kaolinite clay from Nigeria was studied at different initial concentrations and temperatures. The adsorption capacity of clay increased from 3.94 to 8.85 mg g^{-1} by increasing the solution temperature thus suggesting that the adsorption of lead ions on kaolinite clay is an endothermic (Unuabonah *et al.*, 2007a). Adsorption of lead ions on phosphatic clay from USA was investigated using a batch equilibrium technique. The adsorption capacity of lead ions was 32 mg g^{-1} (Singh *et al.*, 2001). Adsorption of lead ions on tripolyphosphate-impregnated kaolinite clay (where kaolinite from Nigeria) was studied as a function of pH of the solution. For example, at pH equal to 4 and with a concentration of 500 mg L^{-1} , the adsorption capacity was 24.7 mg g^{-1}

(Unuabonah *et al.*, 2007b). Hectorite clay from USA and vermiculite clay from Spain were converted to functionalized hectorite and functionalized vermiculite using thiol groups and used to adsorb lead ions from aqueous solution. The maximum adsorption capacity of functionalized vermiculite clay was 33 mg g^{-1} for lead ions and was higher than the maximum adsorption capacity of the functionalized hectorite of 10 mg g^{-1} (Diaz *et al.*, 2007). Three types of Saudi natural clays such as Tabuk, Baha and Khaiber were used to adsorb lead ions from wastewater. The study showed the maximum capacity of Tabuk, Baha and Khaiber clays was 30, 25 and 10 mg g^{-1} , respectively (Al-Jlil and Alsewailem, 2009).

The kinetic and equilibrium parameters are important to design a batch adsorber. The external mass transfer coefficient characterizing the resistance of the hydrodynamic boundary layer can be found from the initial adsorption data. While, the internal mass transfer coefficient can be obtained from the experimental adsorption rate data after the initial period of adsorption. Therefore, a survey of literature showed that single resistance models based on external mass transfer can be used to calculate the external mass transfer coefficient. However, accordingly the internal mass transfer coefficient can be calculated from single resistance models where these diffusion models can be used to describe the pore diffusion resistance or surface diffusion resistance. The diffusion of solute within the pellet through the liquid in the pores, is called pore diffusion. While, the surface diffusion occurs when the solute diffuse within the pellet along the walls of the pores (McKay and Al-Duri, 1990).

The aim of this study is to use Bentonite clay as an adsorbent for the adsorption of chromium and lead ions from wastewater using Saad two series resistance internal diffusion model (STSIRDM) in order to calculate the adsorption time constants and equilibrium parameters required to design a batch adsorber.

MATERIALS AND METHODS

Materials: The adsorbent used in this study is Bentonite clay obtained from Jeddah city, located in the west of Saudi Arabia.

The adsorbate are chromium and lead ions solution prepared from chromium nitrate and lead nitrate purified LR supplied by S.define-chem. Limited (Laboratory Rasayan).

Characterization of Bentonite clay (adsorbent): The chemical analysis of Bentonite clay was done by XRF and presented in Table 1. In addition, the physical properties of Bentonite clay were done by the standard methods as shown in Table 2. The XRD analysis for Bentonite clay was also carried. The XRD analysis confirmed the presence of 80% montmorillonite as a minimum, 10% kaolinite and illite and quartz as 10% as the maximum in Bentonite clay.

Equilibrium experiments: Equilibrium isotherms were determined for Bentonite clay by placing a constant mass of clay (1 g) with 50 mL lead ions solution in glass bottles on an agitation shaker. In each isotherm run, the lead ions solution concentration ranged from $50\text{-}1300 \text{ mg L}^{-1}$. While, the chromium ions solution concentration ranged from $50\text{-}800 \text{ mg L}^{-1}$. A clay particle size of 0.25 mm was used to determine the isotherms. The solution temperature was 20°C . The adsorption process reached to state of equilibrium after 30 min but the equilibrium experiments were run for 3 h to ensure that the adsorption process has attained equilibrium. After that, the samples were filtered using filter papers, then diluted and the absorbance was measured using atomic absorption spectroscopy. Lastly, the absorbance of samples was converted to concentrations using the

Table 1: Chemical analysis of Bentonite clay by XRF

Elements	Content (wt%)
SiO ₂	55.0±3.0
Al ₂ O ₃	22.0±2.0
TiO ₂	1.5±0.25
Fe ₂ O ₃	5.67±0.5
MgO	2.30±0.45
CaO	<2.00
Na ₂ O	< 2.00
K ₂ O	<1.00
P ₂ O ₅	0.20
S O ⁻³	0.002
Cl ⁻	0.2
Cr ₂ O ₃	0.02
Mn ₂ O ₃	0.03
Loss on ignition	9.80

Table 2: Characteristic properties of Bentonite clay

Characteristics	Values
BET surface area (m ² g ⁻¹)	62.5671
Pore volume (p/po = 0.97) (cm ³ g ⁻¹)	0.098005
Average pore width (Å)	62.656
Average pore diameter (Å)	95.650
Porosity (%)	16.7
Solid density (g cm ⁻³)	2.63

calibration curves for lead and chromium ions. The amount of lead and chromium ions adsorption on the clay was calculated from the mass balance equation on the batch reactor as follows:

$$q_e = \frac{V(C_0 - C_e)}{M} \quad (1)$$

where, M is the mass of clay in gram, V is volume of the solution in liter, q_e is the amount of adsorption of ions (mg g⁻¹) C₀ is initial solution concentration of lead and chromium ions (mg L⁻¹) and C_e is the concentration of the lead and chromium ions at equilibrium (mg L⁻¹). The equilibrium adsorption isotherm curves were obtained from the graph of amount of lead and chromium ions adsorption on clay versus the lead and chromium ions concentration as shown in Fig. 1.

Kinetic experiments: The kinetic experiments were performed to obtain the experimental adsorption rates. In these experiments, the lead and chromium ions concentration in the bulk solution decreases over time until it reached to an equilibrium. In the adsorption rate experiment using a specific agitation speed, 1 g mass of clay was added to 50 mL of lead and chromium ions solution separately having a specific initial metal ions solution concentration in bottles placed on the thermostat-controlled shaker. After starting the shaking, a sample of one bottle was taken at different period of times until the end of 3 h time period. This was followed by the filtration of the mixture and the absorbance was measured by atomic absorption spectroscopy. Finally, the absorbance measurements were converted to concentration.

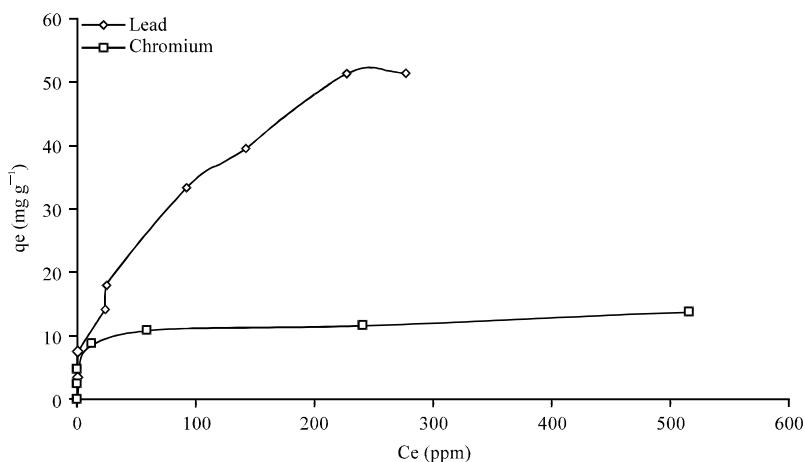


Fig. 1: Equilibrium isotherm for lead and chromium ions on Bentonite clay

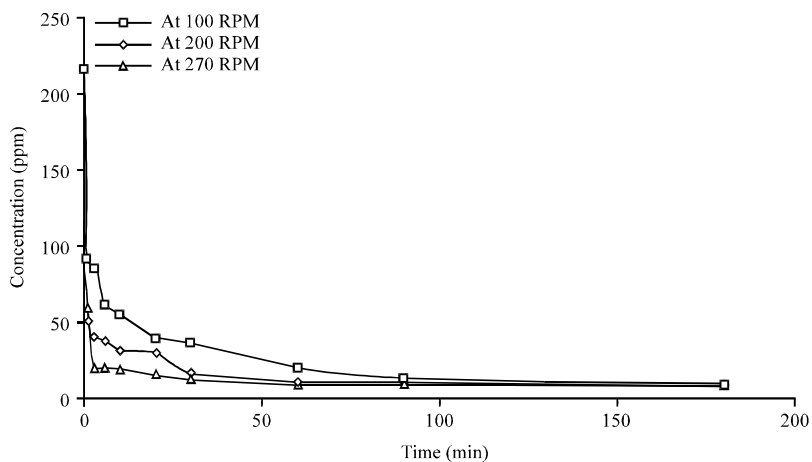


Fig. 2: Effect of different agitation speed on adsorption of lead on Bentonite clay

The effect of the two parameters namely the agitation speed and the initial metal ions (chromium or lead) concentrations was studied to determine the adsorption rate of metal ions on clay.

In these experiments, various runs were carried at different agitation speeds (100, 200 and 270 RPM) to study the effect of agitation speed on the adsorption rate at 20°C. This was done with 1 g mass of Bentonite clay with having a particle diameter of 0.25 mm in 50 mL of metal ions (chromium or lead ions) solution with an initial concentration of 200 mg L⁻¹. In these experimental runs, the initial concentration of chromium and lead ions was kept constant before adding the Bentonite clay mass on the metal (chromium or lead) solution in the bottles. After starting the experiment, samples of metal (chromium or lead ions) solutions were withdrawn at different time intervals during 3 h experimental period, filtrated and concentration was determined by atomic absorption spectroscopy. The experimental data were plotted as concentration versus time as shown in Fig. 2 and 3.

Experimental runs were carried at different initial concentrations of lead ion (154, 216 and 307 mg L⁻¹) to investigate the effect of different initial concentrations on the adsorption rate at

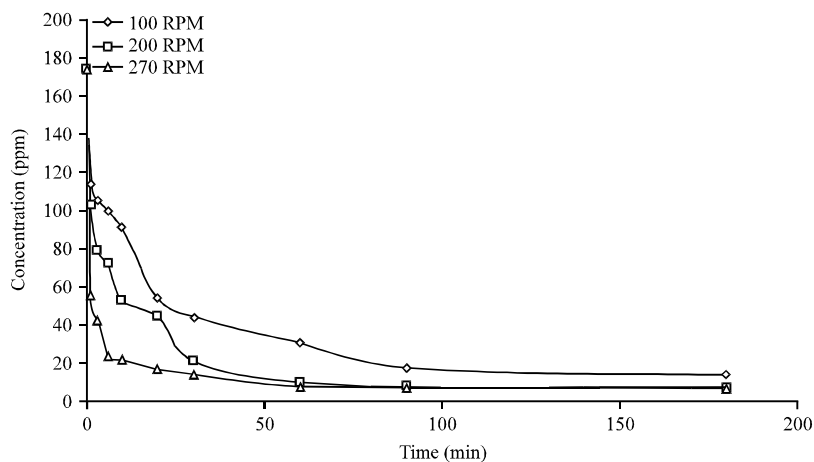


Fig. 3: Effect of different agitation speed on adsorption of chromium on Bentonite clay

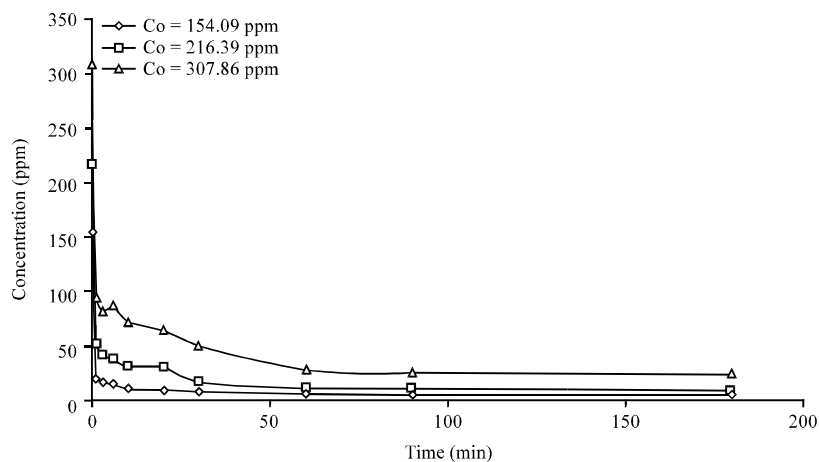


Fig. 4: Effect of different initial concentrations on adsorption of lead on Bentonite clay

20°C. To achieve this, 1 g of Bentonite clay at an agitation speed of 200 RPM was used in 50 mL of lead solution with clay particle diameter of 0.25 mm. The procedure to determine the lead ions concentration in the bulk solution was the same as discussed earlier. The experimental data were plotted as concentration versus time as shown in Fig. 4.

Similarly, experimental runs were carried for chromium at different initial concentrations (94, 174 and 277 mg L⁻¹) to investigate the effect of different initial concentrations on the adsorption rate at 20°C. To achieve this, 1 g of Bentonite clay at an agitation speed of 200 RPM was used in 50 mL of chromium solution with clay particle diameter of 0.25 mm. The procedure to determine the chromium ions concentration in the bulk solution was the same as discussed earlier. The experimental data were plotted as concentration versus time as shown in Fig. 5.

Analysis of equilibrium isothermal model: The Saad Isotherm Model (SIM) was employed in this study. The equilibrium parameters were estimated by correlating the equilibrium equations with data from equilibrium experiments using a nonlinear regression technique (i.e., fminsearch function from MATLAB). Hence, the equilibrium parameters can be used to describe the chromium and lead ions removal by Bentonite clay as an adsorbent in a batch adsorber from wastewater.

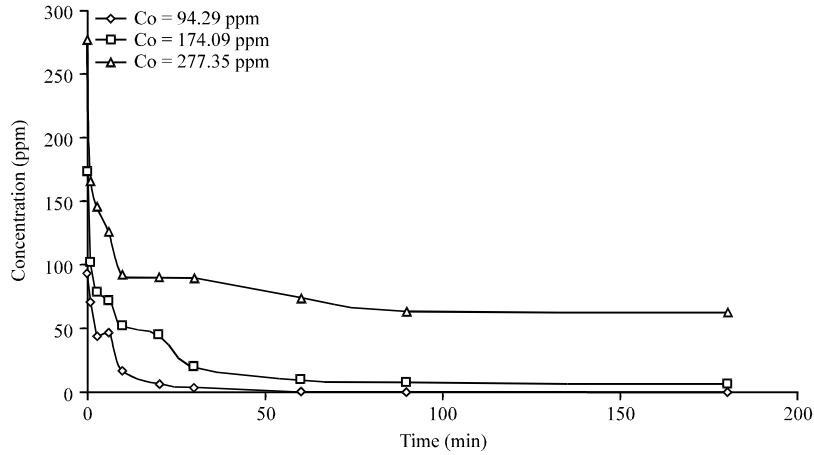


Fig. 5: Effect of different initial concentrations on adsorption of chromium on Bentonite clay

Table 3: Saad equilibrium parameters for the chromium and lead ions adsorption on Bentonite clay

Metal type	K_s (L g ⁻¹)	b_s (L mg ⁻¹)	S	R ²
Chromium	12.4558	1.2378	0.0088	0.9695
Lead	1.0075	0.0204	0.1464	0.9755

Saad Isotherm Model (SIM): This study presented a novel isotherm model, a modification of Langmuir model and used instead of Langmuir model as the Langmuir model cannot fit the experimental data well on a heterogeneous surface. This model was defined as the Saad Isotherm Model (SIM). This model has three parameters and was used to fit the experimental data on heterogeneous surface. The Saad Isotherm Model (SIM) can be written as follows:

$$q_e = \frac{K_s C_e}{[1 + b_s C_e]^{bb}} \quad (2)$$

Where:

$$bb = 1 - S^2 b_s C_e$$

The main advantage of this model is its applicability to equilibrium experiments both on homogeneous and heterogeneous surfaces. Where S is the heterogeneity parameter and when $S = 0$, this model converts to Langmuir model. It is known that, Langmuir model fits the experimental data on homogenous surface very well. At $S < 0$, the model fits the experimental data on heterogeneous surface as found in Table 3.

The Saad parameters K_s , b_s and S were obtained using the non-linear regression technique with Eq. 2.

Data in Fig. 6 and 7 show the non-linear relationship between C_e and q_e for the Bentonite clay. The equilibrium parameters K_s , b_s and S were calculated by non-linear regression technique and presented in Table 3. As shown in Fig. 6 and 7, the Saad equation fits the experimental data very well.

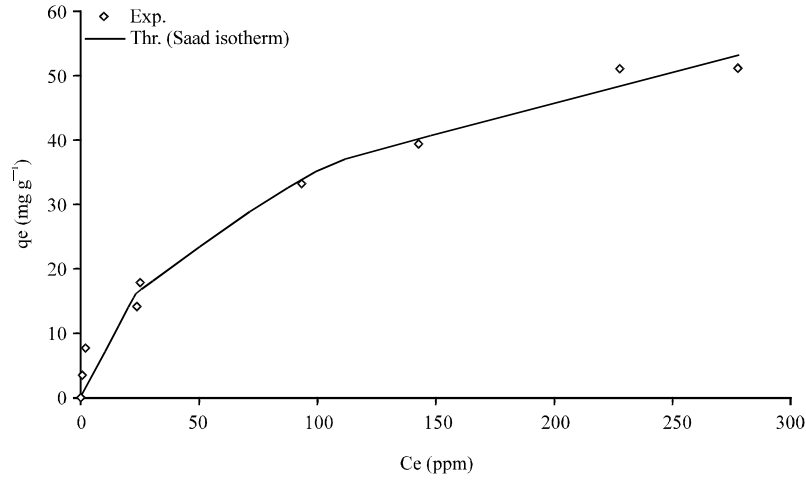


Fig. 6: Equilibrium isotherm data fitting with Saad isotherm model between lead ions and Bentonite clay

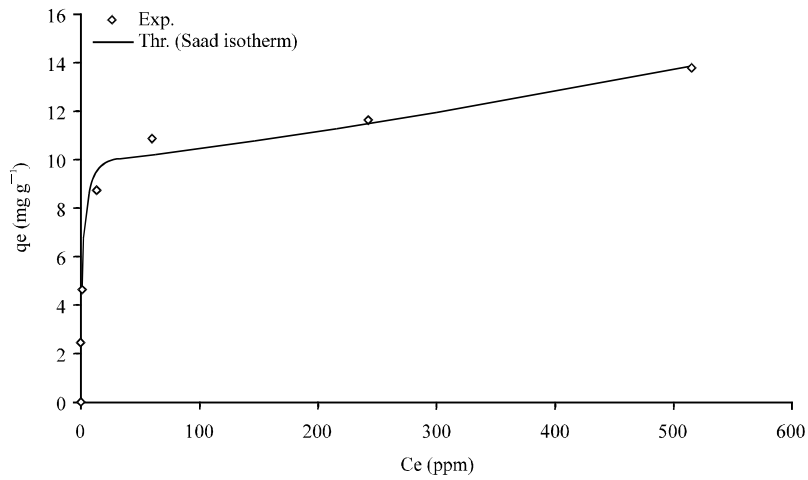


Fig. 7: Equilibrium isotherm data fitting with Saad isotherm model between chromium ions and Bentonite clay

Table 4: Series model parameters for lead ions with Bentonite clay at $C_0 = 216.39$ and 174.09 ppm, agitation speed = 100 RPM

Series model with	Saad isotherm
$C_0 = 216.39$ (ppm)	
K_1	0.0809
K_2	0.0000
F	1.0000
AARD (%)	0.5317
R^2	0.717
$C_0 = 174.09$ (ppm)	
K_1	0.0522
K_2	0.0000
F	1.0000
AARD (%)	0.367
R^2	0.761

Saad Two Internal Series Resistances Model (STISRM): This study presented a novel mass transfer model based on two internal resistances in series with Saad isotherm equation. The model was named as Saad Two Internal Series Resistances Model (STISRM). This model was used to calculate the adsorption rate constants, k_1 and k_2 (1 sec^{-1}) and the adsorption fraction (f) that represents the variations in pore sizes during the adsorption process if the internal mass transfer controls the rate of the adsorption process. It is helpful to use internal mass transfer model as the only rate controlling step for explaining the experimental adsorption rate data after the initial period of adsorption and to calculate the preliminary kinetic parameters. The kinetic parameters can be used to predict the concentration-time curves in the batch adsorber.

Presentation of series model mechanism: The internal layers of the clay particles expand during adsorption causing variations in the pore sizes of clay during the process. In order to examine this mechanism, it is the first initial mass transfer resistances for adsorption namely, the external mass transfer resistance is negligible. This means that the outer surface of the clay is saturated, hence the mass transfer control shifts to the internal pores, e.g., there is diffusion into the pores of clay. The presentation of series model mechanism is shown in Fig. 8.

Mass transfer model based on two internal resistances in series with Saad isotherm equations: The two adsorption rates that occur in series inside the clay particle are represented as follows:

$$f \left(\frac{dq_1}{dt} \right) = k_1 (q_s - q_1) - k_2 (q_1 - q_2) \quad (3)$$

$$(1-f) \left(\frac{dq_2}{dt} \right) = k_2 (q_1 - q_2) \quad (4)$$

The mass balance equation on the batch adsorber is given by:

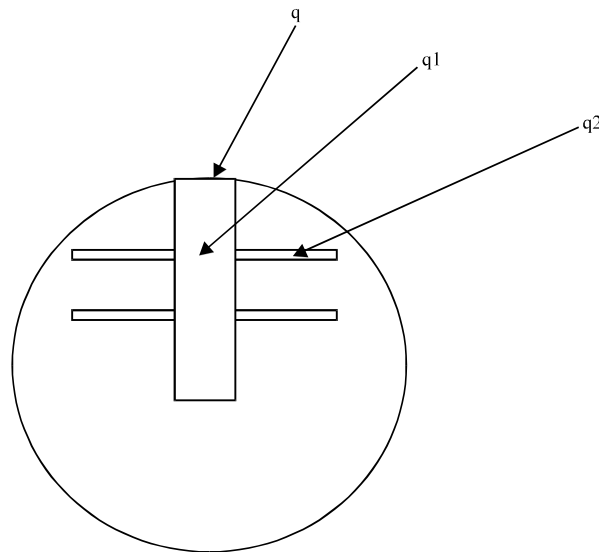


Fig. 8: Presentation of series model mechanism

$$C_o - C_t = M_s (q_1 + q_2) \quad (5)$$

Since there is no external mass transfer resistance, q_s is in equilibrium with C_t . Therefore, the Saad model can be written as follows:

$$q_e = \frac{K_s C_e}{[1 + b_s C_e]^{bb}} \quad (6)$$

Where:

$$bb = 1 - S^2 b_s C_o$$

where, q_s is the adsorbed metal ions concentration on the outer surface (mg g^{-1}). q_1, q_2 is the adsorbed metal ions concentration within the various pores of the clay (mg g^{-1}). C_o is initial concentration of metal ions (mg L^{-1}) and C_t is metal ions concentration in bulk solution at equilibrium (mg L^{-1}). k_1 and k_2 is the adsorption rate constants (1 sec^{-1}), f is the adsorption fraction.

Where:

$$f = \frac{q_1}{q_1 + q_2}$$

By substituting Eq. 6 in Eq. 3, we get:

$$f(dq_1/dt) = k_1 \left(\frac{K_s C_t}{[1 + b_s C_t]^{bb}} - q_1 \right) - k_2 (q_1 - q_2) \quad (7)$$

By rearranging Eq. 7, we get:

$$(dq_1/dt) = \frac{k_1}{f} \left(\frac{K_s C_t}{[1 + b_s C_t]^{bb}} - q_1 \right) - \frac{k_2}{f} (q_1 - q_2) \quad (8)$$

By rearranging Eq. 5, we get:

$$q_2 = (C_o - C_t - q_1 M_s) / M_s \quad (9)$$

By substituting Eq. 9 in Eq. 8, we get:

$$(dq_1/dt) = \frac{k_1}{f} \left(\frac{K_s C_t}{[1 + b_s C_t]^{bb}} - q_1 \right) - \frac{k_2}{f} \left(q_1 - [(C_o - C_t - q_1 M_s) / M_s] \right) \quad (10)$$

By substituting Eq. 6 and 9 in Eq. 4, we get:

$$(1-f) \{d[(C_0 - C_t - q_1 Ms)/Ms]/dt\} = k_2 \{q_1 - [(C_0 - C_t - q_1 Ms)/Ms]\} \quad (11)$$

By rearranging Eq. 11, it yields:

$$\frac{dC_t}{dt} = -\frac{M_s K_2 q_1}{(1-f)} + \frac{k_2}{(1-f)} [C_0 - C_t - M_s q_1] - \frac{K_1 M_s}{f} \left[\frac{C_t K_s}{(1 + b_s C_t)^{bb}} - q_1 \right] + \frac{K_2 M_s}{f} \left[q_1 - \frac{(C_0 - C_t - M_s q_1)}{M_s} \right] \quad (12)$$

By solving Eq. 10 with Eq. 12 simultaneously, we get adsorption rate constants, k_1 and k_2 (1 sec^{-1}) and the adsorption fraction f . In addition, we get the concentration-time curve for the batch adsorber. In this model, the values of M_s (mass of clay per metal ions solution volume) and K_s (the Saad isotherm constant) and b_s is Saad isotherm constant and the initial concentration of metal ions in solution, C_0 was known.

Numerical solution of the non-linear adsorption systems: These ordinary differential equations (Eq. 10 with Eq. 12) were solved simultaneously using ODE15s solver from MATLAB to yield the bulk metal ions concentration-time values. After that, a nonlinear regression method (i.e., `fminsearch` function) from MATLAB was used to find the optimum values of the adsorption rate constants k_1 , k_2 and adsorption fraction f . Then, the average absolute relative percentage deviation (AARD%) between the experimental values and the theoretical values (predicted from the model) is calculated. In addition R^2 is calculated.

RESULTS AND DISCUSSION

The optimum values of the k_1 , k_2 and f and the average absolute relative percentage deviation (AARD%) and R^2 obtained for the various experiments are shown in Table 4-8. Figure 9-18 show the comparison between the experimental data and the predicted bulk concentrations from the Saad series diffusion model with Saad isotherm equations. It was found that, the Saad series diffusion model fits the experimental data well.

Table 5: Series model parameters for lead ions with Bentonite clay at $C_0 = 216.39$ and $C_0 = 174.09$ ppm, agitation speed = 200 RPM

Series model with	Saad isotherm
$C_0 = 216.39$ (ppm)	
K_1	0.2589
K_2	0.0000
F	1.0000
AARD (%)	0.3637
R^2	0.9378
$C_0 = 174.09$ (ppm)	
K_1	0.1311
K_2	0.0000
F	1.0000
AARD (%)	0.4245
R^2	0.7817

Table 6: Series model parameters for lead ions with Bentonite clay at $C_o = 216.39$ and 174.09 ppm, agitation speed = 270 RPM

Series model with	Saad isotherm
$C_o = 216.39$ (ppm)	
K_1	0.2358
K_2	0.0000
F	1
AARD (%)	0.1973
R^2	0.9949
$C_o = 174.09$ (ppm)	
K_1	0.8279
K_2	0.0000
F	1
AARD (%)	0.469
R^2	0.898

Table 7: Series model parameters for lead ions with Bentonite clay at $C_o = 154.09$ and 94.29 ppm, agitation speed = 200 RPM

Series model with	Saad isotherm
$C_o = 154.09$ (ppm)	
K_1	0.2849
K_2	0.0000
F	1.0000
AARD (%)	0.4887
R^2	0.992
$C_o = 94.29$ (ppm)	
K_1	0.0581
K_2	0.0000
f	1.0000
AARD (%)	0.3679
R^2	0.933

Table 8: Series model parameters for lead ions with Bentonite clay at $C_o = 307.86$ and 277.35 ppm, agitation speed = 200 RPM

Series model with	Saad isotherm
$C_o = 307.86$ (ppm)	
K_1	0.2795
K_2	0.0000
F	1.0000
AARD (%)	0.404
R^2	0.7885
$C_o = 277.35$ (ppm)	
K_1	0.3669
K_2	0.0000
f	1.0000
AARD (%)	0.1488
R^2	0.8854

It is clear from the results that the values of adsorption time constant increase with increasing the agitation speed. The clarification occurs from the fact that the adsorption process is a two step mechanism involving external mass transfer in addition to internal mass transfer. Because, the improved agitation speed will reduce the external mass transfer resistance thus allowing the metal

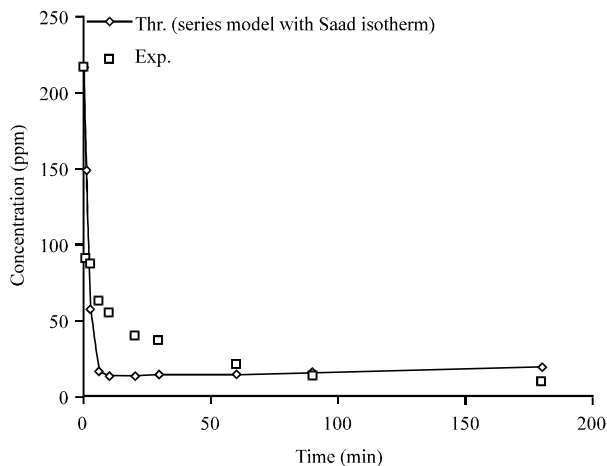


Fig. 9: Series model with Saad isotherm model fit of the kinetic data of lead with Bentonite clay, conditions: $C_o = 216.39$ ppm, agitation speed = 100 RPM

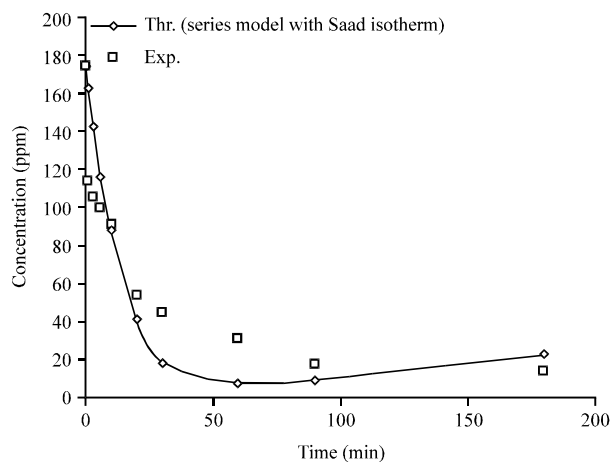


Fig. 10: Series model with Saad isotherm model fit of the kinetic data of chromium with Bentonite clay, conditions: $C_o = 174.09$ ppm, agitation speed = 100 RPM

ions to concentrate at the surface of clay. Therefore, accordingly there will be a greater driving force for internal diffusion resulting in higher values of the adsorption time constants. Similar findings were reported by other researchers (Mckay, 1983).

In addition, there is an increase in the values of adsorption time constant with corresponding increase of the initial metal solution concentrations. This would mean that increasing the concentration of the bulk solution increases the driving force of metal ions from the bulk solution on to clay surface after that into the pores of clay particle. The results agree with those of McKay (1983) who found the same tendency for the adsorption process of metal ions on clay surface.

From Fig. 9-18, it is evident that under different experimental conditions, the external mass transfer controlled the adsorption rate for a short time but after that the major resistance to adsorption was internal diffusion.

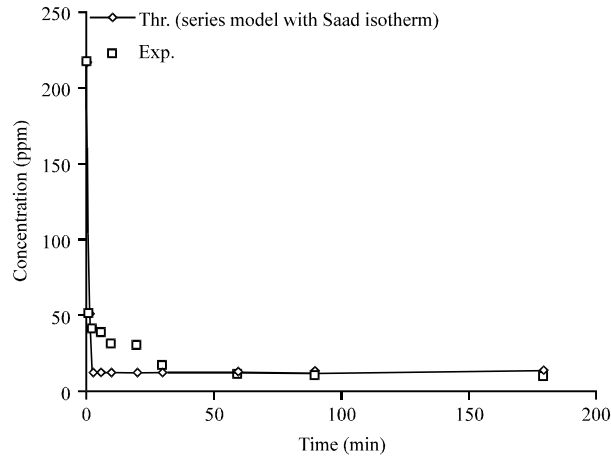


Fig. 11: Series model with Saad isotherm model fit of the kinetic data of lead with Bentonite clay, conditions: $C_0 = 216.39$ ppm, agitation speed = 200 RPM

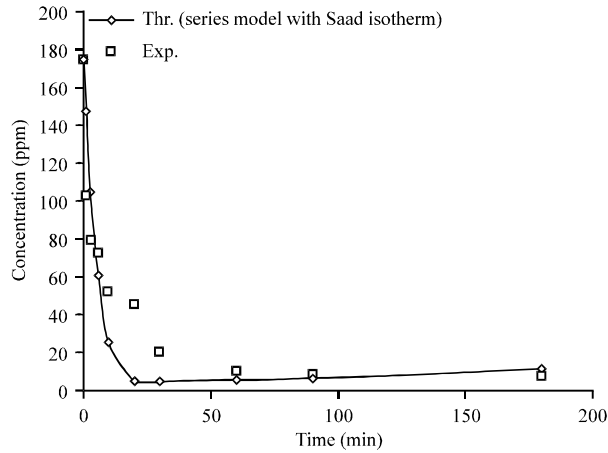


Fig. 12: Series model with Saad isotherm model fit of the kinetic data of chromium with Bentonite clay, conditions: $C_0 = 174.09$ ppm, agitation speed = 200 RPM

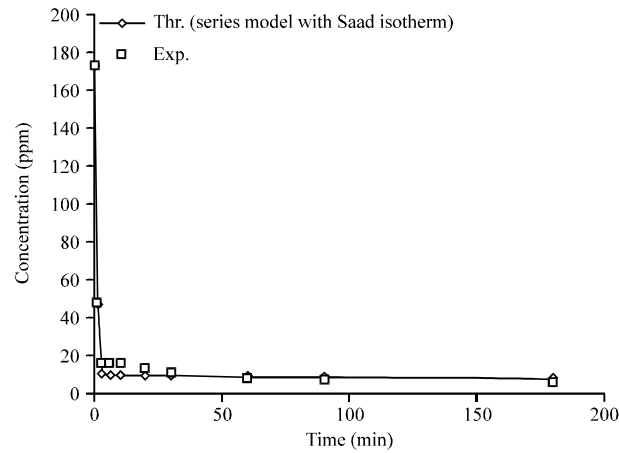


Fig. 13: Series model with Saad isotherm model fit of the kinetic data of lead with Bentonite clay, conditions: $C_0 = 216.39$ ppm, agitation speed = 270 RPM

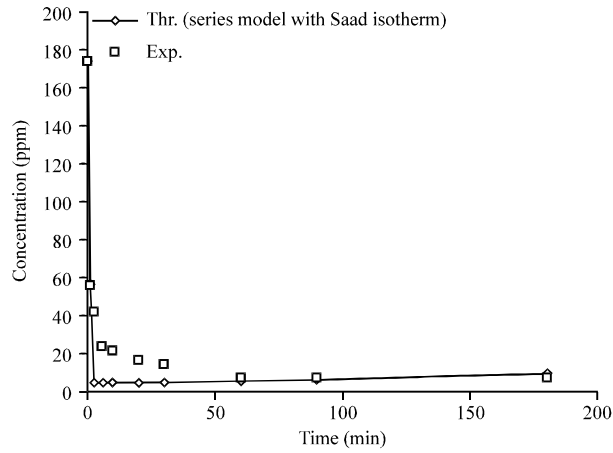


Fig. 14: Series model with Saad isotherm model fit of the kinetic data of chromium with Bentonite clay, conditions: $C_0 = 174.09$ ppm, agitation speed = 270 RPM

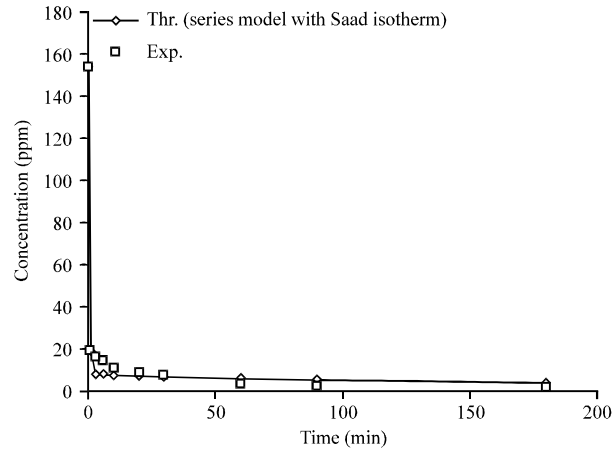


Fig. 15: Series model with Saad isotherm model fit of the kinetic data of lead with Bentonite clay, conditions: $C_0 = 154.09$ ppm, agitation speed = 200 RPM

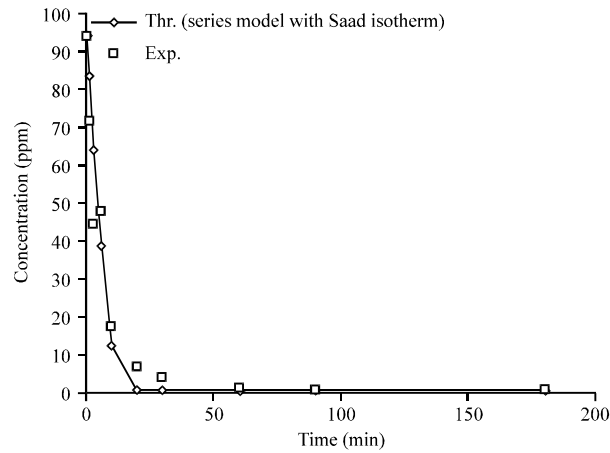


Fig. 16: Series model with Saad isotherm model fit of the kinetic data of chromium with Bentonite clay, conditions: $C_0 = 94.29$ ppm, agitation speed = 200 RPM

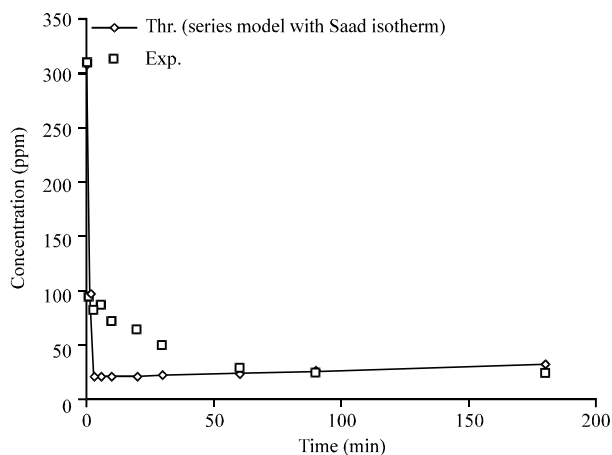


Fig. 17: Series model with Saad isotherm model fit of the kinetic data of lead with Bentonite clay, conditions: $C_0 = 307.86$ ppm, agitation speed = 200 RPM

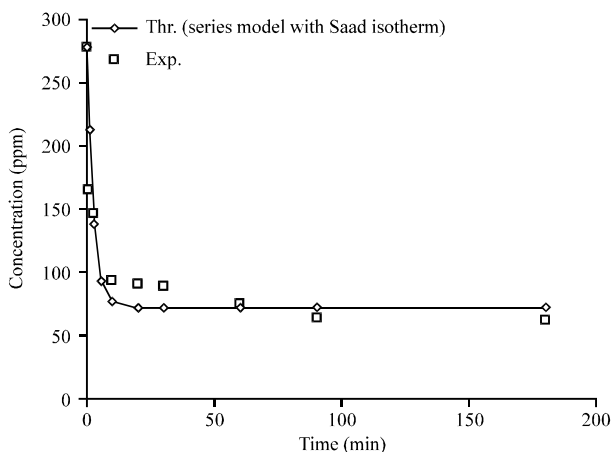


Fig. 18: Series model with Saad isotherm model fit of the kinetic data of chromium with Bentonite clay, conditions: $C_0 = 277.35$ ppm, agitation speed = 200 RPM

CONCLUSION

The study showed that Saad isotherm agreed well with the isotherm experimental data obtained for the adsorption of lead and chromium ions on the surface of Bentonite clay. The internal adsorption time constants were obtained to describe the occurrence of slow rate of ion adsorption after the initial period. Although, most of the ion adsorption on clay surface occurred during the initial period, yet the internal diffusion is the major rate-controlling step in controlling the adsorption rate of lead and chromium ions from wastewater.

REFERENCES

- Al-Jlil, S.A. and F.D. Alsewailam, 2009. Saudi Arabian clays for lead removal in wastewater. *Applied Clay Sci.*, 42: 671-674.
- Diaz, M., P. Cambier, J. Brendle and R. Prost, 2007. Functionalized clay heterostructures for reducing cadmium and lead uptake by plants in contaminated soils. *Applied Clay Sci.*, 37: 12-22.

- McKay, G. and B. Al-Duri, 1990. Study of the mechanism of pore diffusion in batch adsorption systems. *J. Chem. Technol. Biotechnol.*, 48: 269-285.
- McKay, G., 1983. The adsorption of dyestuffs from aqueous solutions using activated carbon. III. Intraparticle diffusion processes. *J. Chem. Technol. Biotechnol.*, 33: 196-204.
- Potgieter, J.H., S.S. Potgieter-Vermaak and P.D. Kalibantong, 2006. Heavy metals removal from solution by palygorskite clay. *Miner. Eng.*, 19: 463-470.
- Quek, S.Y., D.A.J. Wase and C.F. Forster, 1998. The use of sago waste for the sorption of lead and copper. *Water SA*, 24: 251-256.
- Singh, S.P., L. Ma and W.G. Harris, 2001. Heavy metal interaction with phosphatic clay: Sorption and desorption behavior. *J. Environ. Q.*, 30: 1961-1968.
- Unuabonah, E.I., B.I. Olu-Owolabi, K.O. Adebowale and A.E. Ofomaja, 2007a. Adsorption of lead and cadmium ions from aqueous solutions by tripolyphosphate-impregnated Kaolinite clay. *Colloids Surface A: Physicochem. Eng. Aspects*, 292: 202-211.
- Unuabonah, E.I., K.O. Adebowale and B.I. Olu-Owolabi, 2007b. Kinetic and thermodynamic studies of the adsorption of lead (II) ions onto phosphate-modified kaolinite clay. *J. Hazard. Mater.*, 144: 386-395.