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Full Length Research Paper

Predicting chromium (VI) adsorption rate in the treatment of liquid-phase oil-based drill cuttings

Reuben N. Okparanma* and Miebaka J. Ayotamuno

Department of Agricultural and Environmental Engineering, Rivers State University of Science and Technology, Port Harcourt, P.M.B 5080, Rivers State, Nigeria.

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The adsorption rate of chromium (VI) on commercial activated carbon during the treatment of the flocculation effluent of liquid-phase oil-based drill-cuttings has been investigated in terms of contact time and initial chromium (VI) ion concentration. Homogenizing 1 g of the activated carbon with 100 ml of the flocculation effluent of known initial concentrations (1.25 → 6.25 mg/l, in turn) in a flask, at a constant stirring speed of 80 rpm at 25°C for 180 min, the pseudo-second-order kinetics was observed to be more suitable in predicting the adsorption rate of chromium (VI) ion in the treatment process as experimental data fitted the model relatively better than the pseudo-first-order kinetics with $R^2 = 0.9999$. Adsorption took place in two steps: an initial high rate step before reaching a plateau at equilibrium in the low rate step. Equilibrium was attained in a contact time of 60 min and the equilibrium adsorption capacity of the activated carbon was 78.6%. Equilibrium adsorption data fitted the Freundlich isotherm well with $R^2 = 0.981$. The intensity of adsorption was 1.32, which indicates a strongly favourable adsorption. This showed that a large proportion of the chromium (VI) ion was adsorbed at low concentration of the adsorbate in solution.

Key words: Carbon adsorption, kinetic models, drill cuttings, chromium removal.

INTRODUCTION

The injection of the flocculation effluent of liquid-phase oil-based drill-cuttings (LP-OBDC) into the ground, as currently being done by oil drilling and exploration and production (E and P) waste management companies in Nigeria, has been described as the best available technology (BAT) for the disposal of this type of drilling waste (Akinlade et al., 1996). Apart from being heavily laden by suspended matter and oil/grease (Table 1), it has also been observed that this flocculation effluent contains chromium (a pollutant heavy metal) at concentrations that could seriously threaten the life of edaphic systems as well as people who depend on local ground water if it is continually injected into the ground without further remedial treatment measures (Okparanma, 2007). Moreso, conventional methods such as precipita-tion, oxidation and reduction, ion exchange, membrane filtration and evaporation are prohibitively expensive for removing metals from dilute solutions containing 1 to 100 mg/l of dissolved metal (Volesky, 1990). But in the recent past, sorption process has been used to remove heavy metals from different industrial effluents (Ho, 2006; Tsekova et al., 2006; Romero et al., 2006; Wankasi et al., 2006; Abia and Asuquo, 2006; Zou et al., 2007; Parvathi et al., 2007; Igwe and Abia, 2007; Ayotamuno et al., 2007; Gök et al., 2008). The sorption of chromium from

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*Corresponding author. E-mail: rokparanma@yahoo.com.Tel: +234 803 2626 169.

Abbreviations

APHA- American Public-Health Association; ASTM - American Society for Testing and Materials; BAT- Best Available Technology; DPR - Department of Petroleum Resources
FE - Flocculation Effluent ; IRS - Infra-red Spectrophotometer; LP-OBDC -Liquid-Phase Oil-Based Drill-Cuttings; PAC - Powdered Activated-Carbon; THC -Total Hydrocarbon Content; TSS - Total Suspended Solids.

Table 1. Chemical compositions of untreated and flocculation effluent of LP-OBDC.

Parameter	Waste stream		
	Untreated LP-OBDC	**Flocculation Effluent of LP-OBDC**	**DPR (2002) Limits**
Oil/Grease (mg/l)	1,649,724	67,300	10
Total Suspended Solids (mg/l)	13,700	610	30
Chromium (mg/l)	5.26	5.01	0.03
pH	8.5	7.4	7.8

aqueous solutions by activated carbon of none-living biomass origin and microbes alike has also been widely reported (Hussein et al., 2004; Demirbas et al., 2004; Ahalya et al., 2005; Nomanbhay and Palanisamy, 2005; Popuri et al., 2007). But the present study reports about the sorption of chromium by activated carbon from the flocculation effluent of liquid-phase oil-based drill cuttings (LP-OBDC), which is heavily laden by oil/grease and suspended solids (Table 1).

Adsorption is the adhesion of a chemical substance (adsorbate) onto the surface of a solid (adsorbent). The most widely used adsorbent is activated carbon, which is commercially available in two main variants – Norit Row 0.8 Supra and Norit SA4. Activated carbon can be prepared either by physical or chemical means using a variety of starting materials such as coconut shell and shell hull of palm tree (Gueu et al., 2007), water hyacinth ash (Uddin et al., 2007) and cornelian cherry, apricot stone and almond shell (Demirbas et al., 2004). But the most popular source of activated carbon is wood charcoal (Abe, 1988) and wood charcoal has been reported to be chromium-free (Yoshiyuki et al., 2005). Activated carbon has a relatively large surface area to mass ratio of 1091.951 m^2/g and total pore volume to mass ratio of 0.582 cm^3/g. It consists mainly of micro-pores (of pore width; 20Å) with some mesopores of pore width up to 60Å. It is also rich in acidic functional groups with the lactonic group being the most abundant (Gunawan et al., 2007). In carbon adsorption processes, knowledge of the adsorption kinetics (i.e. the rate of solute uptake, which dictates the residence time of sorbed solute at the solid-liquid interface) is important because information from it is an indispensable tool in the large-scale process design (Ho and McKay, 1999a). This study also compares the suitability of two predictive models (i.e. pseudo-first- and pseudo-second-order kinetic models) in analyzing the adsorption rate of chromium (in terms of initial concentration and contact time) onto powdered activated carbon.

MATERIALS AND METHODS

Experiments

This experiment was conducted in two steps: firstly, by mixing 1 g of commercial PAC with 100 ml of the flocculation effluent (FE) of known initial chromium concentration in a flask, using a variable-speed STUART Magnetic Stirrer set at 80 rpm at 25°C. The residual concentration of chromium in solution, (C in mg/l), was measured after different stirring times: 5, 10, 15, 30, 60, 120, and 180 min. By equilibrium of masses, the adsorption q (mg/g) was found for each period. Stirring over time was to enable adsorption equilibrium time to be determined. Secondly, trial runs in equilibrium of adsorption were carried out to determine the performance characteristics of the activated carbon. At 25°C, four different flasks (i.e. contactors) containing 1 g of PAC and 100 ml of the flocculation effluent were stirred in turn during the equilibrium time determined earlier in step 1. Thereafter, four different initial chromium concentrations; 1.25, 2.5, 5.01 and 6.25 mg/l were tested. Finally, the amount of chromium retained in equilibrium q_e (mg/g) was calculated for each contactor.

Laboratory analysis

Total chromium was analyzed using a UNICAM-969 Atomic Absorption Spectrophotometer (AAS) by measuring the light absorbance at a specific wavelength of 357.9 nm according to APHA (1998) method 3111C. A standard solution of chromium was used to calibrate the equipment beforehand. Oil/Grease (i.e. total hydrocarbon content, THC) was analyzed according to ASTM (1999) method D3921 using a SHIMADZU Infra-red Spectrophotometer (IRS) by measuring the light absorbance at the wavelength range of 3333 – 3704 nm. Bonny-Light crude was used to calibrate the equipment beforehand. Total suspended solid (TSS) was analyzed according to APHA (1998) method 2540D. pH was analyzed with a WTW MULTI-340 pH-meter according to APHA (1998) method 4500-H^+.

Theory

To observe the kinetics of the adsorption mechanism of chromium onto the PAC, experimental results were fitted to pseudo-first- and pseudo-second-order kinetic models. Pseudo-first-order kinetic expression, integrated and linearized, according to Lagergren (1898); is given as:

$$\log(q_e - q_t) = \log q_e - \frac{K_1}{2.303}t \tag{1}$$

According to Ho and McKay (1999a), pseudo-second-order kinetic model, integrated and linearized, is given as;

$$\frac{t}{q} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e} \tag{2}$$

The values of the parameters K_1 and K_2 were determined by regression analysis by fitting on a number of experimental data points. Then, q_e was calculated for each model and compared with its experimental value.

Adsorption isotherm is an expression relating the amount of adsorbate and the equilibrium concentration of the solute in the fluid at a given temperature. The Freundlich isotherm is an empirical model, which considers the surface of the adsorbent as heterogeneous and is given by:

$$Q_e = K_F C_e^{1/n} \tag{3}$$

The value of n indicates whether or not the adsorption is favourable. The more favourable the process is, the lower the value of n in the range; [1<n<10]. The parameters K_F, Q_e and n were determined by regression by fitting on a number of experimental data points. The Langmuir's isotherm is a theoretical model, which supposes that the maximum adsorption consists in a saturated monolayer of molecules of adsorbate on the surface of the adsorbent considered as homogenous and is given by:

$$\frac{C_e}{q_e} = \frac{C_e}{Q^o} + \frac{K_L}{Q^o} \tag{4}$$

The parameters Q^o and K_L were determined by regression by fitting on a number of experimental data points. From the Langmuir model, the separation factor r, according to Calvo et al (2001) cited in Rozada et al. (2005), may be given by:

$$r = \frac{1}{1 + K_L C_o} \tag{5}$$

Adsorption is favourable if $r < 1$; unfavourable if $r > 1$; linear if $r = 1$; irreversible if $r > 0$.

RESULTS AND DISCUSSION

Chemical characteristics of the LP-OBDC

Table 1 shows the pertinent chemical characteristics of the LP-OBDC *vis-à-vis* the effluent quality discharge standard of the Department of Petroleum Resources (DPR) of the Nigerian government. As it can be observed from Table 1, all the parameters far exceed the safe limits spelt out by the regulatory body; thereby making the untreated and flocculation effluent of the LP-OBDC unsafe for sub-surface injection.

IR spectra studies

The IR spectra shown in Figure 1a are for the oil/grease (O and G), that is, the total hydrocarbon content (THC) analysis of the untreated LP-OBDC. Comparing this spectra with that in Figure 1b for the blank, it is observed that peaks occurred at 3000 – 2700 cm^{-1}, indicating the presence of oil/grease in the range. Therefore, it can be inferred that absorption occurred in the wavelength range of 3333 – 3704 nm.

Sorption kinetics and effect of contact time on chromium uptake rate

The adsorption rate of chromium (VI) onto powdered activated carbon (PAC) at different initial chromium concentrations is shown in Figure 2. The results show that sorption took place in two steps: a high rate step and a low rate step. In the high rate step, 74% of adsorbent saturation capacity was reached in 10 min of contact; before reaching a plateau at equilibrium in the low rate step. This behaviour is corroborated by the findings of Ho and McKay (1999a; b). Sorption, and indeed sorption equilibrium time, is influenced by contact time, pH, temperature, sorbent concentration, nature of the solute and its concentration (Ho and McKay, 2000). But it has been reported that equilibrium time is in the range of 15 min and 10 days (Aksu and Kutsal, 1991; Nourbakhsh et al., 1994) cited in Cossich (2002). In this study, for the range of initial chromium concentrations tested (1.25 → 6.25 mg/l), it is observed from Figure 1 that equilibrium was reached within a contact time of 60 min. It is further observed from Table 2 that the value of the equilibrium concentration deduced with the pseudo-second-order kinetics (i.e. q_e = 3.96 mg/g) is comparable with its experimental value of 3.94 (mg/g); with the value of the correlation coefficient close to unity (R^2 = 0.9999). On the other hand, the value of the equilibrium concentration deduced with the pseudo-first-order kinetics (q_e = 3.47 mg/g) is quite different from its experimental value of 3.94 (mg/g); with the value of the correlation coefficient far from unity (R^2 = 0.2889). This result shows that experimental data fitted the pseudo-second-order kinetics relatively better than the pseudo-first-order model. By implication, the pseudo-second-order model may be more suitable in predicting chromium (VI) adsorption in the treatment process. Demirbas et al. (2004) reported a similar result for chromium (VI) adsorption onto the activated carbon prepared from cornelian cherry, apricot stone and almond shell. Furthermore, a number of sorption systems for chromium (VI), which followed the pseudo-second-order kinetics has been widely reported (Ho and McKay, 1999a).

Adsorption capacity of the powdered activated carbon (PAC) at equilibrium

Equilibrium adsorption capacity of the PAC at the adsorbent dose of 10 g/l of effluent is shown in Table 3; where it is observed that the PAC adsorbed the highest amount of chromium of 1.60 mg/g (representing 64% adsorption) at an initial chromium concentration, C_0 of 2.50 mg/l. This

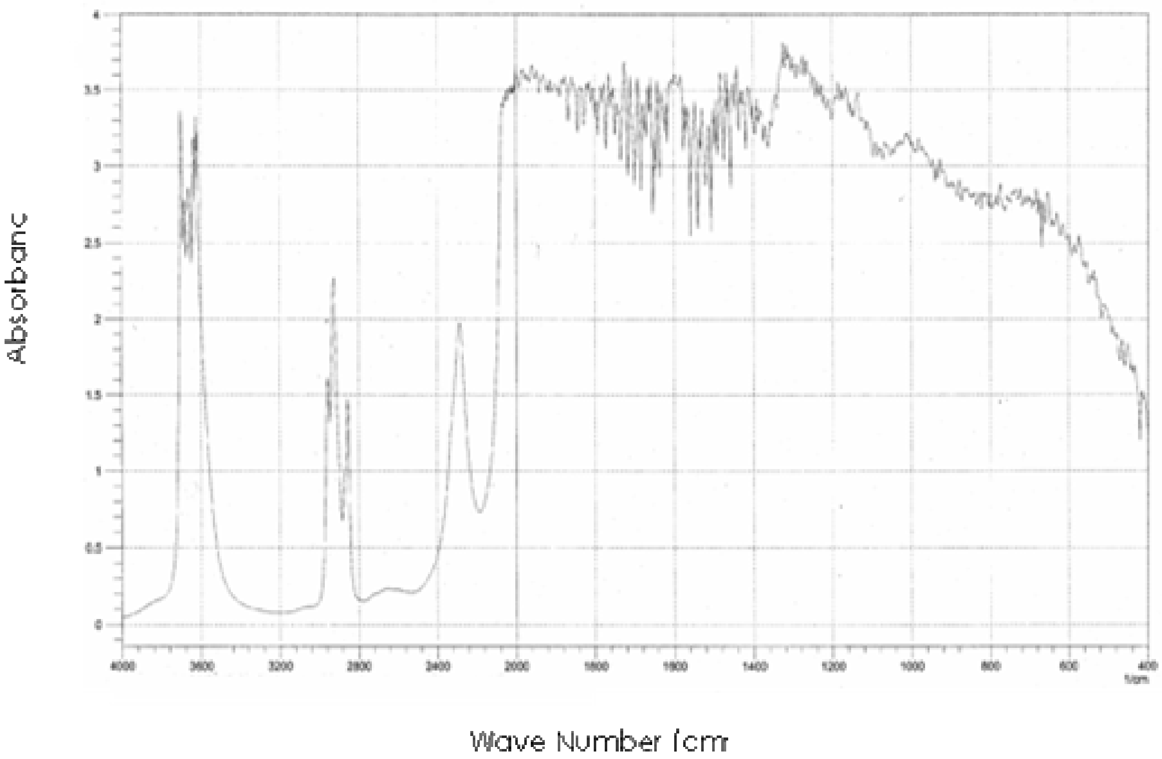

Figure 1a. IRS spectra for the untreated liquid-phase oil-based drill cuttings (LP-OBDC).

Table 2. Comparison of kinetics parameters for Cr^{6+} adsorption in the treatment of the flocculation effluent of LP-OBDC.

Pseudo-first order kinetics	Pseudo-second order kinetics
$K_1 = 9.84 \times 10^{-5}$ (min^{-1})	$K_2 = 3.664 \times 10^{-1}$ (g/mgmin)
q_e (experimental) = 3.94 (mg/g)	q_e (experimental) = 3.94 (mg/g)
q_e (calculated) = 3.47 (mg/g)	q_e (calculated) = 3.96 (mg/g)
$R^2 = 0.2889$	$R^2 = 0.9999$

result indicates a high adsorbate loading at a low initial adsorbate concentration, which, according to Ahalya et al. (2006), is partly due to the availability of sufficient binding sites in the biomass to bind metal ions when present in few numbers. Table 4 compares the Freundlich and Langmuir isotherm parameters. Although the values of the parameters n and r of the Freudlich and Langmuir models respectively point to the fact that the adsorption was favourable, it is observed from Table 4 that experimental data fitted the Freundlich isotherm (Figure 3) relatively better than the Langmuir isotherm (Figure 4); with the correlation coefficient of the former being closer to unity than that of the latter. As stated earlier, a strongly favourable adsorption indicates that a large proportion of chromium (VI) is adsorbed at a very low initial chromium concentration in solution. The maximum equilibrium adsorption capacity of 3.94 mg/g (representing 78.6% equilibrium adsorption capacity) reported in this study is comparable with those reported by other researchers as shown in Table 5.

Conclusion

The adsorption of chromium (VI) onto powdered activated

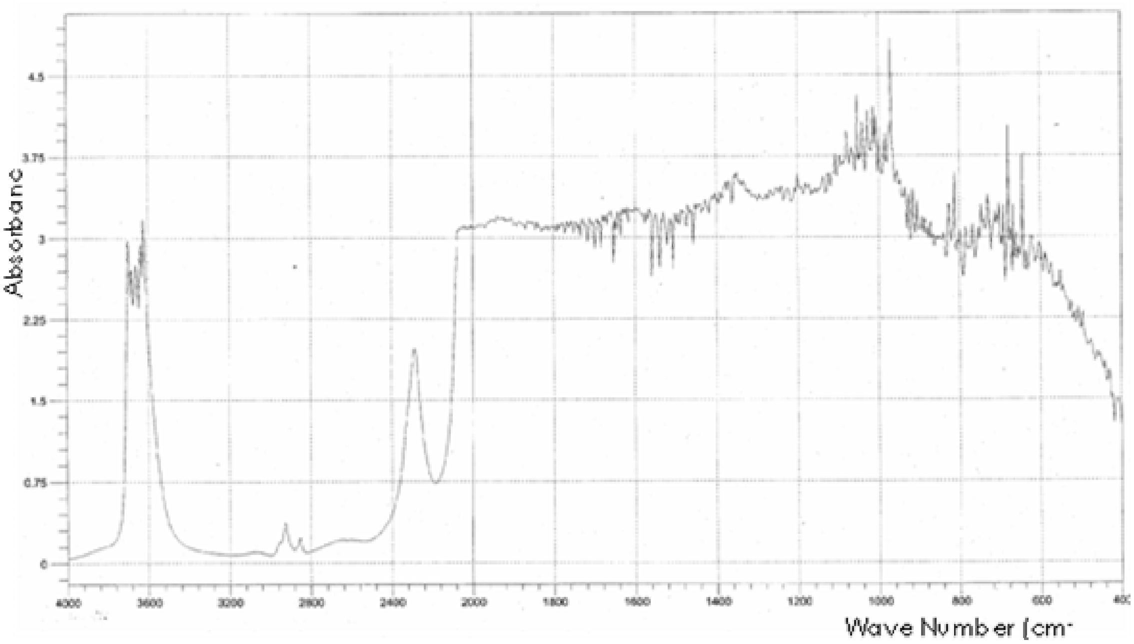

Figure 1b. IRS spectra for blank solution.

Table 3. Equilibrium adsorption capacity of the PAC at 10g of PAC per litre of effluent.

C_o (mg/l)	C_e (mg/l)	$Q_e = C_o - C_e$ (mg/g)
1.25	0.94	0.31
2.50	0.90	1.60
5.01	3.59	1.42
6.25	3.36	2.89

Table 4. Comparison of isotherm parameters for Cr^{6+} adsorption in the treatment of the flocculation effluent of LP-OBDC.

Freundlich isotherm	Langmuir isotherm
$K_F = 0.768$ ($mgl^{1/n}/g.mg^{1/n}$)	$K_L = 17.825$ mg/l
$Q_e = 3.94$ (mg/g)	$Q^o = 10.81$ mg/g
n = 1.32	r = 0.01
$R^2 = 0.981$	$R^2 = 0.6113$

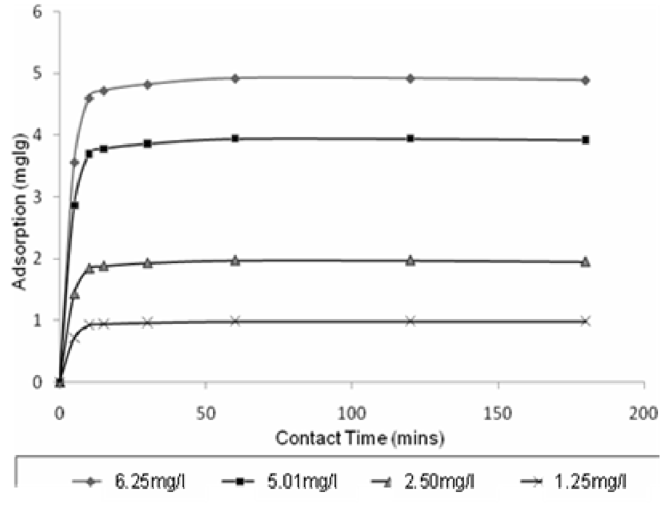

Figure 2. Adsorption rate of Cr^{6+} onto PAC at different initial Cr^{6+} concentrations for the flocculation effluent of LP-OBDC.

carbon (PAC) in the tertiary treatment of the flocculation effluent of liquid-phase oil-based drill-cuttings (laden by suspended matter and oil/grease) fitted the pseudo-second-order kinetics relatively better than the pseudo-first-order kinetics with $R^2 \approx 1.00$. This shows that the pseudo-second-order kinetics could be used to predict chromium (VI) adsorption onto the PAC in the treatment process. Adsorption kinetics (in terms of initial chromium concentration and contact time) took place in two steps: an initial high rate step and a low rate step before reaching a plateau at equilibrium. The high rate step reached 74% of adsorbent saturation capacity in a con-tact time of 10 min. Equilibrium was reached in a contact time of 60 min. The equilibrium concentration of the chromium (VI) at the adsorbent dose of 10 g/l of effluent was 3.94 mg/g,

Table 5. Comparison of sorption capacities of different adsorbents for Cr^{6+}.

Adsorbent	Waste water	Adsorption Capacity (%)	Reference
Sargassum sp.	Aqueous solution of Cr^{3+}	60.0	Cossich et al (2002)
Pseudomonas sp.	Waste water	38.0	Hussein et al (2004)
Activated Carbon	Aqueous solution of Cr^{6+}	99.9	Demirbas et al (2004)
Activated Carbon	Aqueous solution of Cr^{6+}	99.9	Ahalya et al (2005)
Activated Carbon	Aqueous solution of Cr^{6+}	52.0	Nomanbhay and Palanisamy (2005)
Activated Carbon	Flocculation effluent of LP-OBDC	78.6	This study

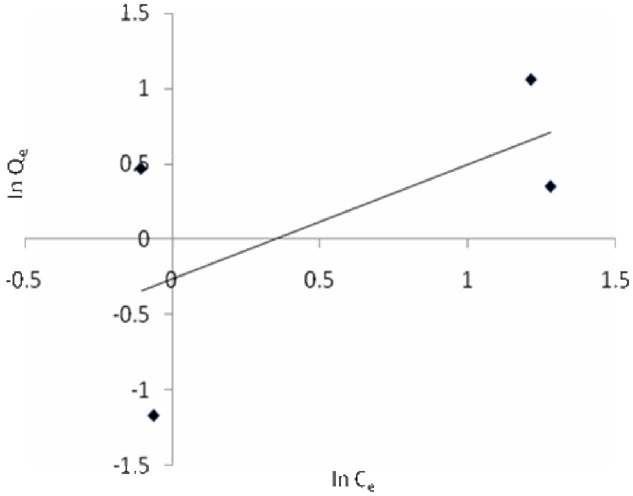

Figure 3. The Freundlich isotherm for PAC.

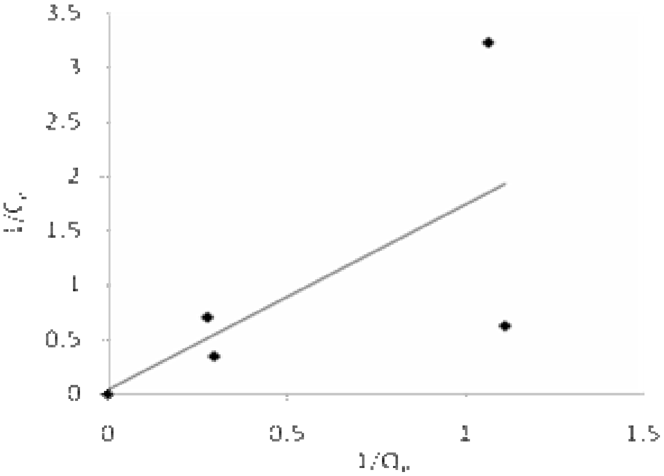

Figure 4. The Langmuir isotherm for PAC.

which shows that the PAC was able to adsorb up to 78.6% of the chromium (VI) at equilibrium. Equilibrium adsorption capacity data fitted the Freundlich isotherm relatively better than the Langmuir isotherm with $R^2 = 0.981$. The adsorption intensity constant, $n = 1.32$, which shows that the adsorption was strongly favourable.

Nomenclature

C = Concentration in the liquid phase over a time period t (mg/l)
C_e = Concentration in the liquid phase at equilibrium (mg/l)
C_0 = Initial concentration (mg/l)
K_1 = Pseudo-first order kinetic constant (in min^{-1}) for the adsorption
K_2 = Pseudo-second order kinetic constant for the adsorption (g/mg.min)
K_F = Freundlich constant indicating the capacity of adsorption (in $mgl^{1/n}/g.mg^{1/n}$)
K_L = Langmuir constant related with affinity for the adsorption sites (in mg /l)
n = Dimensionless constant indicating intensity of adsorption
q = Adsorption over a time period t (mg/g)
q_e = Adsorption at equilibrium (mg/g)
Q_e = Adsorption capacity at equilibrium (in mg/g)
Q^o = The maximum adsorption capacity per unit of mass of adsorbent for a complete monolayer on the surface (in mg/g)
r = Separation factor (dimensionless)
R^2 = Correlation Coefficient (dimensionless)
t = Time (min)

REFERENCES

Abe F (1988). Themo-chemical Study of Forest Biomass. Bulletin of Forest and Forest Production Resources Institute. 352: l - 95.
Abia AA, Asuquo ED (2006). Lead (II) and nickel (II) adsorption kinetics from aqueous metal solutions using chemically modified and

unmodified agricultural adsorbents. Afr. J. of Biotech. 5(16): 1475 - 1482.

Ahalya N, Kanamadi RD, Ramachandra TV (2005). Biosorption of chromium (VI) from aqueous solution by the husk of Bengal grain (*Cicer arientinum*).Electron. J. of Biotechnol. 8(3): 258 – 264.

Akinlade MO, Adenipekun A, Wind JA (1996). Drilling Residue Disposal: SPDC-E Approach. Proceedings of the 20th Annual International Conference and Exhibition of the Society of Petroleum Engineers-Nigeria Council, Warri, Nigeria. 25 - 27 September. pp. 65 - 74.

Aksu Z, Kutsal T (1991). A bio-separation process for removing lead (II) ions from waste water by using *C. vulgaris*. J. of Chem. Technol. and Biotechnol. 52(1): 109 -118.

American Standards for Testing and Materials (ASTM) (1999) *Water (II)*.11.02; 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428 – 2959.

American Public Health Association (APHA) (1998) Standard Methods for the Examination of Water and Wastewater. (20th ed.). 1015 Fifteenth Street, NW Washington, DC 20005 – 2605.

Ayotamuno MJ, Okparanma RN, Ogaji SOT, Probert SD (2007). Chromium removal from flocculation effluent of liquid-phase oil-based drill-cuttings using powdered activated carbon. J. of Applied Energy. 84(10): 1002 – 1011.

Calvo LF, Otero M, Moran A, Garcia AI (2001). Upgrading sewage sludges for adsorbent preparation by different treatments. J. of Bioresource Technol. 80; 143 - 148.

Cossich ES, Tavares CRG, Ravagnani TMK (2002). Biosorption of chromium (III) by *Sargassum sp*. Biomass. Electron. J. of Biotech. 5(2); [Online] Available: http://www.bioline.org/html (25th January 2008).

Demirbas E, Kobya M, Senturk E, Ozkan T (2004). Adsorption kinetics for the removal of chromium (VI) from aqueous solutions on the activated carbon prepared from agricultural wastes. Water SA. 30(4); 533 – 539.

Department of Petroleum Resources (DPR) (2002). Environmental Guidelines and Standards for the Petroleum Industry in Nigeria. Ministry of Petroleum and Natural Resources, Abuja, Nigeria. 314pp.

Ho YS, McKay G. (1999a). Pseudo-Second-Order Model for Sorption Processes. J. of Process Biochem. 34; 451 – 465.

Ho YS, McKay G. (1999b).The sorption of lead (II) ions on peat. J. of Water Res. 33(2); 578 – 584.

Ho YS, McKay G (2000).The kinetics of sorption of divalent metal ions onto Sphagnum moss peat. J. of Water Res. 34(3); 735 – 742.

Ho YS (2006). Second-order kinetic model for the sorption of cadmium onto tree fern: a comparison of linear and non-linear methods. J. of Water Res. 40; 119 – 125.

Gok O, Ozcan AS, Ozcan A (2008). Adsorption kinetics of naphthalene onto organo-sepiolite from aqueous solutions. J. of Desalination. 220; 96 – 107.

Gueu S, Yan B, Adouby K, Ado G (2007). Kinetics and thermodynamics study of lead adsorption onto activated carbon from coconut and seed hull of the palm tree. Int. J. of Environ. Sci. and Technol. 4(1); 11 – 17.

Gunawan CM, Indraswati N, Ismadji S (2007). Improved adsorption capacity of commercially available activated carbon Norit Row 0.8 Supra with thermal treatment for phenol removal. J. of Environ. Protection Sci. 1; 62 -74.

Hussein H, Ibrahim FS, Kandeel K, Moawad H (2004). Biosorption of heavy metals from waste water using *Pseudomonas sp*. Electron. J. of Biotechnol. 7(1); 38 - 46.

Igwe JC, Abia AA (2007). Equilibrium sorption isotherm studies of Cd (II), Pb (II) and Zn (II) ions detoxification from waste water using unmodified and EDTA-modified maize husk. Electron. J. of Biotechnol. 10(4); 536 – 548. MMM M

Lagergren S (1898). Zur Theorie Der Sogenannten Adsorption Gelöster Stoffe *Kungliga Svenska Vetenskapsakademiens. Handlingar*, Band 24, No. 4, 1-39.

Nomanbhay MS, Palanisamy K (2005). Removal of heavy metals from industrial waste water using chitosan-coated oil palm shell charcoal. *Electronic J. of Biotechnol.* 8(1); 43 – 53.

Nourbakhsh M, Sag Y, □zer D, Aksu Z, Caglar A (1994). A comparative study of various biosorbents for removal of chromium (VI) ions from industrial waste water. J. of Process Biochem. 9; 1 – 5.

Okparanma RN (2007). Investigation into the Potential use of Activated Carbon in the Removal of Heavy Metals from Liquid-Phase Oil-Based Drill Cuttings (LP-OBDC). M.Tech. Thesis. Department of Agricultural and Environmental Engineering, Rivers State University of Science and Technology, Nkpolu, Port Harcourt. Nigeria.

Parvathi K, Nagendran R, Hareshkumar R (2007). Lead biosorption onto waste beer yeast by-product, a means to decontaminate effluent generated from battery manufacturing industry. Electron. J. of Biotechnol. 10(1); 1 – 14.

Popuri RS, Jamala R, Reddy SK, Abburi K (2007). Biosorption of hexavalent chromium using tamarind (*Tamarindus indica*) fruit shell – a comparative study. Electron. J. of Biotechnol. 10(3); 358 – 367.

Romero MC, Reinoso EH, Urrutia MI, Kieman AM (2006). Biosorption of heavy metal by *Talaromyces helicus*: a trained fungus for copper and biphenyl detoxification. Electron. J. of Biotechnol. 9(3); 221 -226.

Rozada F, Otero M, Moran A, Garcia AI (2005). Activated carbons from sewage sludge and discarded tyres: production and optimization. J. of Hazardous Materials; [Online] Available: http://www.elsevier.com/locate/jharzmat (19th January 2006).181-191.

Tsekova K, Christova D, Ianis M (2006). Heavy metal biosorption sites in *Penicilium cyclopium.* J. of Applied Sci. and Environ. Manage. 10(3); 117 – 121.

Uddin MT, Islam MS, Abedin Z (2007). Adsorption of phenol from aqueous solutions by water hyacinth ash. J. of Engineering and Applied Sci. 2(2); 11 – 17.

Volesky B (1990). Biosorption of heavy metals. CRC Press, Boston, USA. 408p.

Wankasi D, Horsfall M, Spiff AI (2006). Sorption kinetics of Pb^{2+} and Cu^{2+} ions from aqueous solution by Nipah palm (*Nypa fruticans*) shoot biomass. *Electronic* J. of Biotechnol. 9(5); 587 – 592.

Yoshiyuki S, Masaru Y, Takanori S (2001). Effective Utilization of Waste Products for Agriculture Based on Carbonization. Paper presented at the 2001 American Society of Agricultural Engineers (ASAE) Annual International Meeting, Sacramento, California, USA. 30th July - 1st August.

Zou W, Cheng S, Han R (2007). Kinetics of methylene blue biosorption by phoenix tree's leaves powder. Life Sci. J. 4(1): 89 – 93.