

Removal of chromium and strontium from aqueous solutions by adsorption on laterite

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Abstract: To investigate the adsorptive properties of a local laterite deposited in Chenzhou, Hunan province, China, the adsorptive properties of the natural laterite were investigated by batch technique in this study. The effects of contact time, pH, ionic strength, temperature, and the concentration on adsorption properties were also analyzed. The obtained experimental results show that the main mineral composition of laterite is kaolinite and montmorillonite. The adsorption process achieved equilibrium within 60 minutes and 90 minutes for Sr(II) and Cr(VI), respectively. The adsorption capacities for Cr(VI) and Sr(II) by the laterite were about 7.25 mg·g⁻¹ and 8.35 mg·g⁻¹ under the given experimental conditions, respectively. The equilibrium adsorption data were fitted to the second-order kinetic equation. The adsorption capacity for Sr(II) onto the laterite increased with increasing pH from 3–11 but decreased with increasing ionic strength from 0.001 to 1.0 M NaCl. The Sr(II) adsorption reaction on laterite was endothermic and the process of adsorption was favored at high temperature. Similarly, the adsorption capacity for Cr(VI) onto the laterite increased with increasing pH from 3–11, however, the ionic strength and temperature had an insignificant effect on Cr(VI) adsorption. The adsorption of Cr(VI) and Sr(II) was dominated by ion exchange and surface complexation in this work. Furthermore, the Langmuir and Freundlich adsorption isotherm model was used for the description of the adsorption process. The results suggest that the studied laterite samples can be effectively used for the treatment of contaminated wastewaters.

Introduction

The increase in environmental contamination as a consequence of industrial development is a challenge that the society must face (Iriel et al. 2018, Jabłońska-Czapla et al. 2014, Kamagate et al. 2018). For instance, heavy metal ions are frequently found in surface and subsurface water sources originating from landfill leachates (Christensen et al. 2001, Kamagate et al. 2018, Nayanthika et al. 2018), mine tailings disposal sites or near the low-level radioactive waste repositories (Duda 2014). The adsorption and migration of heavy metals in soils and clay minerals have received more and more attention because most of them do not undergo degradation. What is more, the removal of these heavy metals has a huge effect on the environment (Nayanthika et al. 2018).

Heavy metal ions mentioned above are non-biodegradable and, hence, are accumulated by living organisms causing a large number of diseases and disorders (He et al. 2019). Therefore, the development of efficient techniques for the removal of heavy metals from waters and wastewaters is an important task in terms of protection of public health and

environment. Migration of these heavy metal contaminants can be prevented by either remediation/removal strategies or isolation. Conventional technologies such as precipitation, co-precipitation, ion exchange, adsorption (Özcan et al. 2009, Sudha et al. 2018, Suponik and Lutyński 2009), solvent extraction and reverse osmosis (Bhattacharyya and Gupta 2008), electro dialysis, electrochemical reduction (Balkaya and Cesur 2008), membrane technology (Atalay et al. 2009) and evaporation removal (Pérez-Marín et al. 2007) have been developed for the removal of metal ions from aqueous solutions. Among typical methods for waste water treatment, adsorption with solid adsorbents is an effective method because of its high efficiency, low cost, availability, profitability and convenience to use (Adebowale et al. 2006, Bhattacharyya and Gupta 2008, Chávez et al. 2010, Glocheux et al. 2013, Nayanthika et al. 2018).

The removal of metals from water can be performed by means of adsorption on filter materials (Reddy et al. 2014) while clay liners are commonly used as engineered barriers in landfills to prevent leachate migration and groundwater contamination (Cuevas et al. 2012, Duda 2014). Clay minerals, due to their

large surface area and high cation exchange capacity, have been studied for potential applications as environmental remediation agents and in the removal of heavy metals and organic contaminants from water (Li and Gallus 2007, El-sayed et al. 2019). The ability of the bottom liner to adsorb heavy metals becomes a significant design issue. Therefore, the adsorption properties of natural clays are thus of fundamental importance in evaluating their potential use as landfill barrier material (Du and Hayashi 2006, Kaoser et al. 2005, Koutsopoulou et al. 2010, Sanchez-Gimenez et al. 2012, Sezer et al. 2003).

Clay minerals such as zeolite (Lv et al. 2014), montmorillonite (Akar et al. 2009, Orta et al. 2019), bentonite (Chen et al. 2012, Chen et al. 2015, Guerra et al. 2014, He et al. 2016, Mesci 2011) etc. are well regarded as efficient adsorbents for the treatment of heavy metals-containing wastewater. Therefore, smectite-rich clays are the most widely used clay liners due to their low hydraulic conductivity values, high ion exchange capacity (CEC), large specific surface area (SSA), selectivity and regenerability (Chen et al. 2013, Churchman et al. 2006).

Many factors influence the adsorption capacity such as pH, ionic strength, humic substances, temperature, contaminants concentration, chemical and mineralogical nature of adsorbents and chemical species of cations, etc. In this regard, various investigations (Bhattacharyya and Gupta 2008, Chen et al. 2015, Ghaemi et al. 2011, Iriel et al. 2018, Smičiklas et al. 2007) have been conducted. Recently, the adsorptive behaviors of Cr(VI) (Bayrak et al. 2006, Gładysz-Płaska et al. 2012, Ji et al. 2015, Li et al. 2012, Saravanan et al. 2019) and Sr(II) (Ghaemi et al. 2011, Lalmunsiama et al. 2015, Wallace et al. 2012, Zhao et al. 2014) on natural clays or their modified adsorbent have been investigated.

Chromium (Cr) is used in many industrial processes, such as plating, alloying, tanning of animal hides, and as a water corrosion inhibitor. Chromium will cause various diseases and severe risk (Deveci and Kar 2013). Strontium (Sr) is one of

the products of nuclear fission in radioactive waste effluents resulting from reprocessing of nuclear fuels (Ahmadpour et al. 2010). And which is one of the most frequently found radionuclides in the soil and groundwater at nuclear weapon test sites and nuclear waste repositories (He et al. 2016). However, few studies are focus on the adsorption capacity of Cr(VI) or Sr(II) on laterites in the literature.

The objectives of the present work are to (a) study the effect of contact time, pH, ionic strength and temperature on the adsorption of Cr(VI) and Sr(II) on laterite; (b) determine the Cr(VI) and Sr(II) thermo-dynamic models and adsorption isotherms, and simulate the experimental data with different adsorption models.

Materials and methodology

Materials

The laterite used in this study was sampled in ChenZhou, Hunan province, China, 300 km south from Changsha (Fig. 1). Some basic properties of this material are listed in Table 1. The bulk chemical components of the sample were analyzed using the X-ray fluorescence spectrometry (Netherlands, AXIOS mAX) as follows: O 49.6%, Si 19.4%, Al 14.5%, Fe 7.0%, C 6.0%, K 1.3%, Mg 0.9%, Ti 0.7%, Na 0.6%. The adsorption capacity of adsorbent is mainly controlled by its cation exchange capacity (CEC) and specific surface area (SSA). Based on the test's methods by American Society for Testing Materials (ASTM), the CEC of laterite used in this work is 25.0 mmol·100 g⁻¹ and the SSA is 48.5 m²·g⁻¹. Meanwhile, the mineral composition and environmental conditions also have important effects on the adsorption of adsorbent. The mineral composition of the laterite and the environmental conditions including the temperature, the pH value and the ionic strength on the adsorption will be discussed in this work.

Before the adsorption test, the used natural laterite was dried in an oven at 55°C for 48 h. After cooling on a metal



Fig. 1. Sampling location and image of raw laterite sample

plate, the dried sample was transferred to a mortar and grinded. Then, the grinded laterite powder was sieved using a 0.16 mm aperture sieve.

The grain size distribution of laterite was investigated by an automatic laser particle size analyzer (Beckman Coulter LS230). The measuring range was $4.0 \cdot 10^{-5}$ –2.0 mm. The powdered laterite sample was pressed in stainless steel sample holders for XRD analysis. A Dmax 12 kW rotating anode X-ray diffractometer, D8 FOCUS (Germany, Bruker), which operates at 100 mA and 40 kV, was employed. XRD analysis was performed with $\text{CuK}\alpha$ radiation ($\lambda=0.15418$ nm). The measurement range was from 3 to 70° , with a scanning rate 8° per minute. The JCPDS PDF database was used for the phase identification.

The laterite used in this work presents a grain size distribution smaller than 0.160 mm diameter (D) as shown in Fig. 2.

The X-ray pattern of the laterite is shown in Fig. 3. The characteristic diffraction peaks of the plane at 6.25° , 19.96° , 20.89° and 59.93° , and the corresponding basal spacing of 14.12, 4.48, 4.25 and 1.54 Å, respectively, indicate that the compound in the samples used in the present work was montmorillonite (M). The characteristic diffraction peak of the plane at 12.22° and the corresponding basal spacing of 7.24 Å also show the kaolinite (K) compound in the sample used. The peaks at 26.62° , 35.50° and 50.17° represented the presence of quartz (Q: 3.35, 2.56 and 1.82 Å) as impurity. The peaks at 25.05° , 33.89° and 68.20° represented the presence of quartz orthoclase (O). What is more, the peaks at 42.54° and 39.50° represented the presence of iron silicate (IS) and potassium-aluminum silicate (PAS), respectively.

Stock solutions of Cr(VI) and Sr(II) with the concentration of $1.0 \text{ g}\cdot\text{L}^{-1}$ were prepared from nitrate and potassium dichromate, respectively. Fresh dilutions were used for each experiment. The conductivity of distilled water used in this test was $\text{EC} \leq 4 \text{ mS}\cdot\text{cm}^{-1}$. All the chemicals used were in analytical grade.

Adsorption experiments

The adsorption experiments of Cr(VI) and Sr(II) from their aqueous solution systems on laterite were undertaken using a batch equilibrium technique in triplicate with a constant solid to liquid ratio of 1:100 as recommended by Putthividhya (2008), Mohapatra et al. (2009), etc. All experiments were performed under aerobic conditions and with chemicals of analytical purity. The adsorption capacity of Cr(VI) or Sr(II) onto the laterite was investigated by using batch technique in polyethylene centrifuge tubes sealed with a screw cap under ambient conditions. The laterite samples weighing 2 g were added to 200 ml of adsorbate aqueous solution in an incubator shaker (THZ-320), respectively. The pH values of the system were adjusted by using $0.01 \text{ mol}\cdot\text{L}^{-1}$ HCl or $0.01 \text{ mol}\cdot\text{L}^{-1}$ NaOH to obtain the desired values, which were determined by a pH meter (Mettler Toledo, FE20K). The ionic strengths were adjusted with 0.001 M or 1.0 M NaCl solution to the desired values. The experimental conditions such as contact time, pH, ionic strength, temperature and concentrations were selected on the basis of previous work related to the adsorption of some heavy metal ions (Chen et al. 2012). Shaking time of the adsorption equilibrium was determined by the adsorption kinetics studies. Except when pH effect was studied, all experiments were carried out at initial $\text{pH}=7.0 \pm 0.02$. No

Table 1. Basic properties of the tested soil

Sample	Natural water content [%]	Natural dry density [$\text{g}\cdot\text{cm}^{-3}$]	Natural void ratio	G_s	Clay/Silt [%/%]	c [kPa]	φ [$^\circ$]
Laterite	37.14	1.35	0.96	2.65	69/31	19–40	18.5–19.0

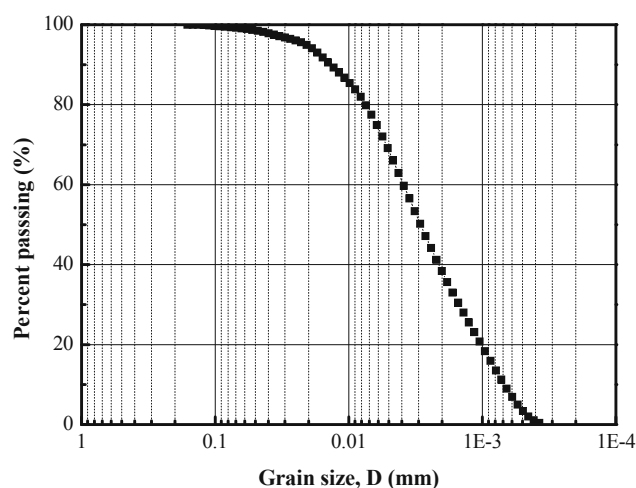


Fig. 2. Grain size distribution of laterite sample

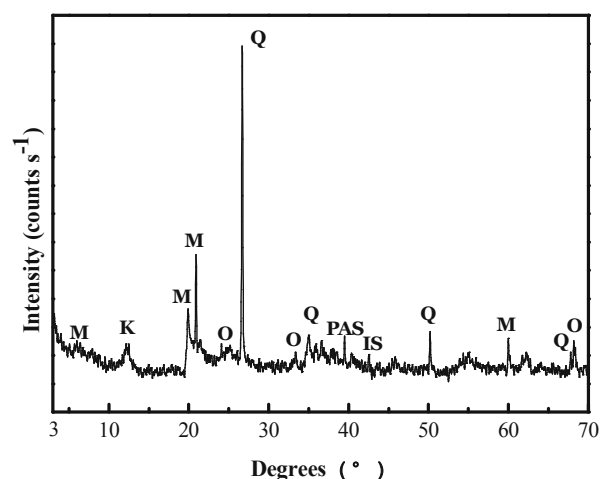


Fig. 3. XRD pattern of natural laterite, M – montmorillonite, Q – quartz, K – kaolinite, O – orthoclase, IS – iron silicate, PAS – potassium-aluminum silicate

additional sodium chloride was added except for the study of the effect of ionic strength on the adsorption. Adsorption isotherms were obtained with adsorbate initial concentrations ranging from 50 mg·L⁻¹ to 600 mg·L⁻¹ at 298±1 K, respectively. When adsorption equilibrium was reached, the solid and the liquid phases were separated by centrifugation at 9000 rpm for 15 minutes. The concentrations of Cr(VI)/Sr(II) solution before and after adsorption were measured by using an inductively coupled plasma optical emission spectrometry, ICP-OES (America, PerkinElmer).

All experimental data were the average of duplicate or triplicate determinations. The relative uncertainties of the data amount to 5%.

The amount of metal ions absorbed onto the laterite, derived from the initial and the equilibrium concentrations, c_0 and c_e , could be expressed as Eq. 1:

$$Q_e = \frac{(c_0 - c_e) \cdot v}{m} \quad (1)$$

The removal or uptake efficiency (%) of Cr(VI)/Sr(II) by the laterite was calculated from the difference between the initial and the final concentrations using the equation:

$$\text{Removal (\%)} = \frac{c_0 - c_e}{c_0} \cdot 100\% \quad (2)$$

Equilibrium distribution coefficient (K_d , L·mg⁻¹) used extensively for charactering various heavy metal ions adsorption and desorption, was calculated as:

$$K_d = \frac{Q_e}{C_e} \quad (3)$$

where Q_e (mg·g⁻¹) is the amount concentration of Cr(VI)/Sr(II) onto the laterite, c_0 (mg·L⁻¹) is the initial concentration of Cr(VI)/Sr(II) in suspension, c_e (mg·L⁻¹) is the concentration of Cr(VI)/Sr(II) in supernatant after centrifugation, m (g) is the mass of the adsorbent, and V (L) is the volume of the Cr(VI)/Sr(II) solutions.

Results and discussion

Adsorption kinetics

The adsorptions of Cr(VI) and Sr(II) by the laterite were examined at different time intervals and the results are shown in Figs. 4 and 5. It is easily seen from Figs. 4 and 5 that the amount of adsorption increased with the contact time. The maximum adsorption capacity for Cr(VI) and Sr(II) was observed after 90 minutes and 60 minutes, respectively, beyond which there was almost no further increase in the adsorption. Therefore, these two times were considered to be needed to reach equilibrium. Similarly, the adsorption of metal ions such as Cr onto laterite also occurred quickly and 60 minutes' shaking time was found to be appropriate for maximum adsorption (Syama et al. 2015).

The practical application of clay and clay minerals for heavy metal ions removal requires the knowledge of process kinetics. The process kinetics describes the solute uptake rate, offering the estimated residence time required to achieve a definite extent of heavy metal ions removal. The two most widely adopted adsorption kinetics are pseudo-first-order and pseudo-second-order. The pseudo-second-order equation is often successfully used to describe the kinetics of the adsorption process on heavy metal ions. Its expression is as follows:

$$\frac{dQ_e}{dt} = k_2 \cdot (Q_e - Q_t)^2 \quad (4)$$

where k_2 (g·mg⁻¹·min⁻¹) is the second-order rate constant and Q_t (mg·g⁻¹) denotes the amount of Cr(VI)/Sr(II) adsorbed at time t (min). This equation can be integrated for the boundary conditions $t = 0$ ($Q_e = 0$) to $t = t$ ($Q_t = Q_e$) and then linearized, leading to Eq. 5:

$$\frac{t}{Q_t} = \frac{1}{2 \cdot k_2 \cdot Q_e^2} + \frac{t}{Q_e} \quad (5)$$

By plotting t/Q_t versus t , a straight line is obtained with the slope of $1/2 \cdot k_2 \cdot Q_e^2$ and intercept of $1/Q_e$ (Fig. 4b). The values of k_2 and Q_e are given in Table 2. The high correlation coefficient

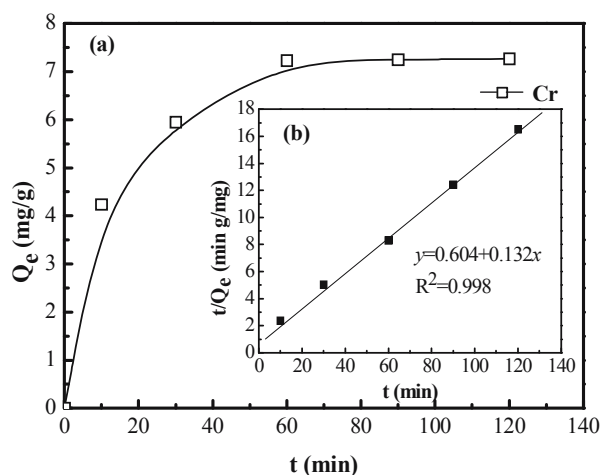


Fig. 4. (a) Effect of shaking time on Cr(VI) adsorption onto laterite; (b) The pseudo-second-order equation of t/Q_e versus t

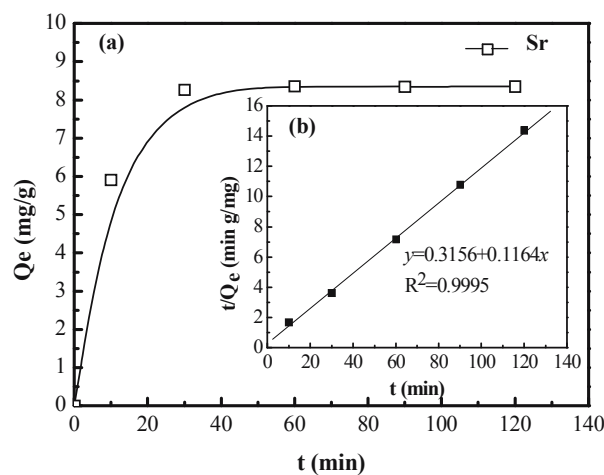


Fig. 5. (a) Effect of shaking time on Sr(II) adsorption onto laterite; (b) The pseudo-second-order equation of t/Q_e versus t

indicates the applicability of the pseudo-second order rate model to describe the adsorption process. Similar results are also reported by Syama et al. (2015) who used the laterite in the removal of chromium. The results of this study show that the adsorption capacity of laterite to heavy metal ions (Cr(VI)/Sr(II)) is weaker than that of bentonite or puresorbe (Table 2).

The effect of pH on the adsorption of Cr(VI) and Sr(II) ions

The removal of Cr(VI)/Sr(II) increases gradually from pH 3.0–7.0 and maintains a high level around pH 7.0 and does not change considerably at high pH values (Fig. 6). A maximum removal of Cr(VI) and Sr(II) by the laterite is observed at alkaline condition. The results also show that the laterite has a higher adsorption capacity of Sr(II) than that of Cr(VI). This phenomenon can be attributed to the ionic potential and hydrated ionic radius of metal ions (Silveira et al. 2003).

At low pH, H^+ was prior adsorbed on laterite and thus causing competition with Cr(VI)/Sr(II); excess H^+ took over the reactive adsorption sites on surface and also restrained the bonding of Cr(VI)/Sr(II) (Wu et al. 2012). At high pH, OH^- would promote the adsorption of Cr(VI)/Sr(II) by neutralizing the produced H^+ in reaction. Those ion competitions for adsorption sites were all attributed to ion exchange mechanism (Chen et al. 2012, He et al. 2016). Meanwhile, a small

contribution of surface complexation has to be accounted for pH value higher than 8 (Missana and García-Gutiérrez 2007). What is more, precipitation of $Cr(OH)_3$ or $SrCO_3$ may also occur above $pH=7$, resulting in a decrease of heavy metal ions in aqueous systems. Similar results are also reported by Chairidchai and Ritchie (1990), Khan et al. (1995) and Anjos et al. (2014) who used laterite, bentonite, montmorillonite and vermiculite as the adsorbent for Zn(II), Sr(II) and Cr(VI) adsorption in their studies, respectively.

The effect of ionic strength on the adsorption of Cr(VI) and Sr(II) ions

In this study, the effect of initial ionic strength on Cr(VI) and Sr(II) adsorption onto the laterite is achieved by varying the concentration of additive NaCl from 0.001 to 1.0 M. As shown in Fig. 7, the adsorption of Sr(II) onto the laterite is obviously affected by ionic strength. The adsorption decreases with increasing NaCl concentration, which suggests that the Na^+ greatly affects Sr(II) adsorption. The uptake of Sr(II) from aqueous solution changes from about 97% to 48% when the ionic strength increases from 0.001 to 1.0 M. However, the adsorption behavior with ionic strength is different for Sr(II) and Cr(VI). The ionic strength has an insignificant effect on the removal efficiency of Cr(VI) in contrast to the case of Sr(II).

Table 2. Parameters of the pseudo-second-order for the Cr(VI)/Sr(II) adsorption on laterite

Heavy metal ions	Adsorbent	pH	Experimental (Q_e) [$mg \cdot g^{-1}$]	Pseudo-second-order kinetics			Reference
				k_2 [$g \cdot mg^{-1} \cdot min^{-1}$]	Q_e [$mg \cdot g^{-1}$]	R^2	
Cr(VI)	Laterite	7.0	7.2	0.0144	7.6	0.99	This work
Sr(II)	Laterite	7.0	8.3	0.0215	8.6	0.99	This work
Cr(VI)	Puresorbe	7.0	49.5	0.0018	51.8	0.99	Nityanandi and Subbhuraam 2009
Sr(II)	Bentonite	7.0	9.7	0.0055	10.4	0.99	He et al. 2016

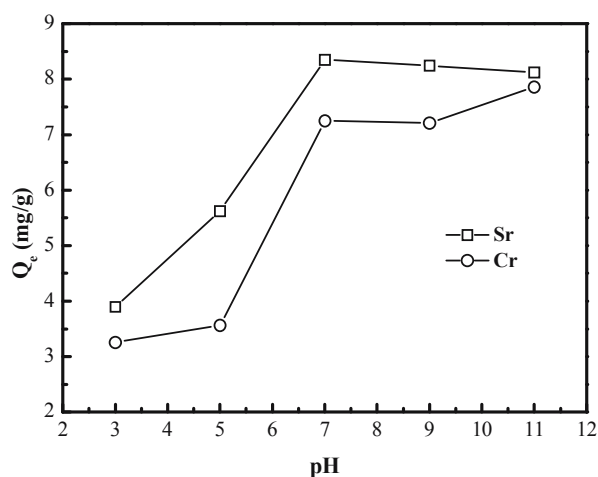


Fig. 6. Effect of pH on Cr(VI) and Sr(II) adsorption onto laterite

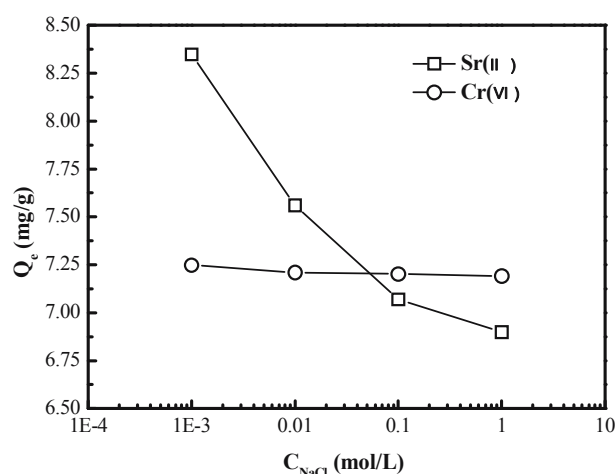


Fig. 7. Effect of ionic strength on Cr(VI) and Sr(II) adsorption onto laterite

The effect of temperature on the adsorption of Cr(VI) and Sr(II) ions

The effect of temperature on the adsorption of Cr(VI) and Sr(II) onto laterite is included in Fig. 8. It can be found that the adsorption capacity of Sr(II) increases, as the temperature in solution increases, suggesting that the adsorption process is endothermic. While, the temperature has insignificant effect on Cr(VI) adsorption. What is more, the K_d value of Sr(II) decreases, as the concentration of Sr(II) increases in solution in contrast to Fig. 8.

The thermodynamic parameters such as enthalpy change (ΔH°), entropy change (ΔS°) and free energy change (ΔG°) are obtained from adsorption experiments at various temperatures (298, 308 and 318 K) and estimated using Eqs. 3, 6, 7 (Raouf and El-Kamash 2006):

$$\Delta G^\circ = -RT \ln K_d \quad (6)$$

$$\ln K_d = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT} \quad (7)$$

where K_d is the equilibrium constant, R ($8.314 \text{ J K}^{-1} \cdot \text{mol}^{-1}$) is the gas constant and T (K) is temperature. The values of ΔH° and ΔS° are obtained from the slope and intercept of Van't Hoff plot of $\ln K_d$ versus $1/T$. The thermodynamic parameters obtained from the Cr(VI) and Sr(II) adsorption onto laterite are shown in Table 3. The positive value of ΔH° confirms the

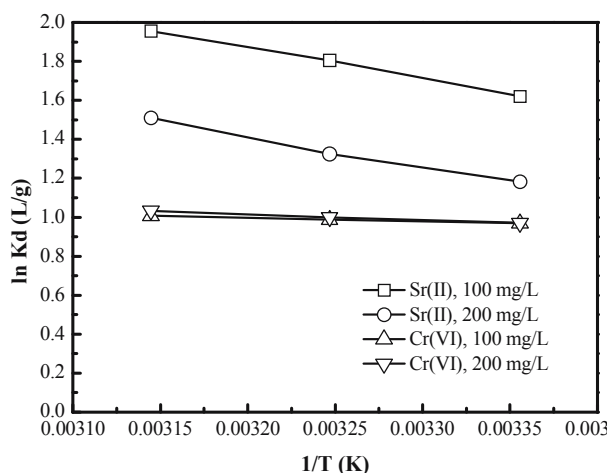


Fig. 8. Effect of temperature on Cr(VI) and Sr(II) adsorption onto laterite

endothermic reaction of the Sr(II) adsorption process. Similar results are also reported by Mohapatra et al. (2009), Seyram (2014), who found that the sorption capacity for Pb(II) and As(III) on laterite increases with temperature, respectively.

The isotherms of the adsorption of Cr(VI) and Sr(II) ions

The effect of Cr(VI) and Sr(II) concentration on its adsorption was studied under the optimized conditions of shaking time (60 minutes and 90 minutes for Sr(II) and Cr(VI), respectively), pH (7.0), volume of aqueous solution (200 mL) and amount of adsorbent (2.0 g). The concentration of Cr(VI) and Sr(II) varied from 50 to 600 $\text{mg} \cdot \text{L}^{-1}$ after proper dilution of the Cr(VI) and Sr(II) stock solutions. The adsorption isotherm of Cr(VI) and Sr(II) on the laterite is shown in Fig. 9.

The general adsorption isotherms that can be used for describing the adsorption include the Langmuir and Freundlich type. The Langmuir model is the simplest and the most commonly used model to represent the adsorption from a liquid phase by a solid phase. The Freundlich isotherm is an empirical equation which can be used to describe heterogeneous systems (Boddu et al. 2003, Suponik et al. 2017).

The equilibrium data for Cr(VI) and Sr(II) over a concentration range from 50 to 600 $\text{mg} \cdot \text{L}^{-1}$ have been correlated with the Langmuir isotherm. The following form of the Langmuir equation was used for this purpose:

$$Q_e = \frac{Q_0 b C_e}{(1 + b C_e)} \quad (8)$$

or, in linear form

$$\frac{t}{Q_t} = \frac{1}{2 \cdot k_2 \cdot Q_e^2} + \frac{t}{Q_e} \quad (9)$$

where Q_e is the amount of solute adsorbed per unit weight of adsorbent after equilibrium ($\text{mg} \cdot \text{g}^{-1}$), c_e is the equilibrium concentration of metal ions remaining in the bulk solution ($\text{mg} \cdot \text{L}^{-1}$), Q_0 and b are Langmuir constants related to adsorption capacity and adsorption energy, respectively. Q_0 , the maximum adsorption capacity, is the amount of metal ions at complete monolayer coverage ($\text{mg} \cdot \text{g}^{-1}$), and b ($\text{L} \cdot \text{mg}^{-1}$) is a constant related to the heat of adsorption [$b a \exp(-\Delta G/RT)$], where ΔG is the Gibbs free energy change ($\text{kJ} \cdot \text{mol}^{-1}$), R is the universal gas constant ($8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$), T is the absolute temperature in Kelvin (K). The constants of the Langmuir isotherm can be obtained by plotting c_e/Q_e versus c_e . The Langmuir isotherms of Cr(VI) and Sr(II) onto laterite are shown in Fig. 10. The linear

Table 3. Thermodynamic parameters of Cr(VI) and Sr(II) adsorption onto laterite

Ions	Concentration [$\text{mg} \cdot \text{L}^{-1}$]	ΔH [$\text{kJ} \cdot \text{mol}^{-1}$]	ΔS [$\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$]	ΔG [$\text{kJ} \cdot \text{mol}^{-1}$] / T[K]		
				298K	308K	318K
Cr(VI)	100	1.53	13.19	-2.40	-2.53	-2.66
	200	2.42	16.19	-2.41	-2.56	-2.73
Sr(II)	100	13.23	57.88	-4.01	-4.62	-5.17
	200	12.90	53.05	-2.93	-3.39	-3.99

plot of c_e/Q_e versus c_e with $R^2=0.99$ and $R^2=0.99$ for Cr(VI) and Sr(II), respectively. A plot of c_e/Q_e against c_e shows that the adsorption seems to follow the Langmuir isotherm.

The adsorption data was also tested for the Freundlich adsorption isotherm equation. The following form of the Freundlich equation was used for this purpose:

$$Q_e = k_F c_e^{1/n} \quad (10)$$

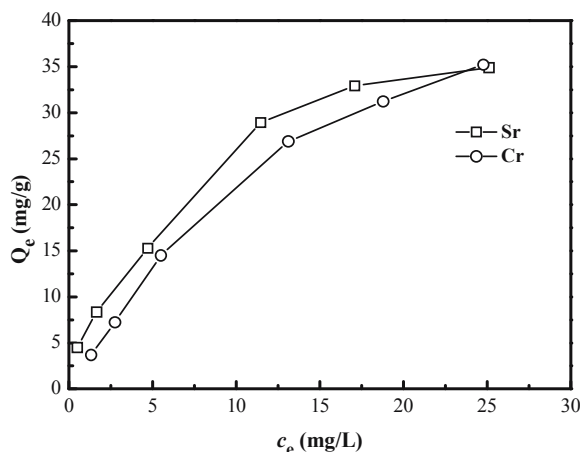


Fig. 9. Adsorption isotherms of Cr(VI) and Sr(II) onto laterite

or, in linear form

$$Q_e = \frac{Q_0 b c_e}{(1 + b c_e)} \quad (11)$$

where k_F is the constant indicative of the relative adsorption capacity of the adsorbent ($\text{mg}^{1-1/n} \cdot \text{L}^{1/n} \cdot \text{g}^{-1}$) and $1/n$ is the constant indicative of the intensity of the adsorption. A plot of $\log Q_e$ against $\log c_e$ gives a straight line, the slope and the intercept of which correspond to $1/n$ and $\log k_F$, respectively. The Freundlich isotherms of Cr(VI) and Sr(II) onto laterite are shown in Fig. 11. The magnitude of the constant k_F provides quantitative information on the relative adsorption affinity towards the adsorbed cations, and the magnitude of constant $1/n$ is an indicator of linearity of adsorption (Chen et al. 2015). The large value of k_F indicates that laterite has a high adsorption affinity towards Sr(II) (Tajar et al. 2009).

The Langmuir isotherm and Freundlich isotherm model parameters for the adsorption of Cr(VI) and Sr(II) on laterite are summarized in Table 4.

Research results show that both Langmuir and Freundlich isotherm model can satisfactorily describe the adsorption of Cr(VI) and Sr(II) on laterite, as indicated by the numerical values of the correlation coefficients (R^2). Similar results are also reported by Zhou et al. (2000), Zhang et al. (2011) and Nga (2013) for Cr(VI), phosphorus and Cu(II), Pb(II) and Cd(II) adsorption on laterite, respectively.

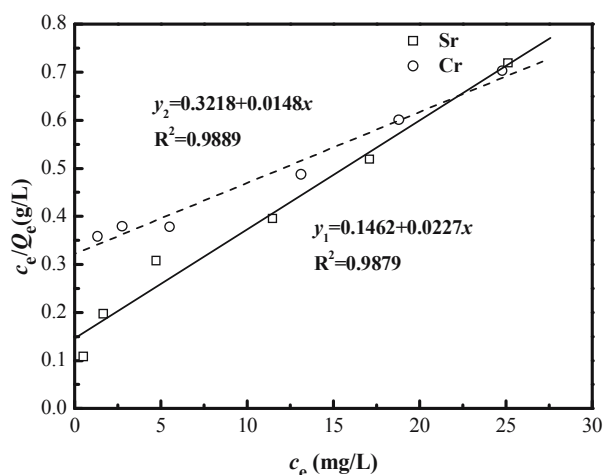


Fig. 10. Fitting curve of the Langmuir adsorption isotherm of Cr(VI) and Sr(II) onto laterite

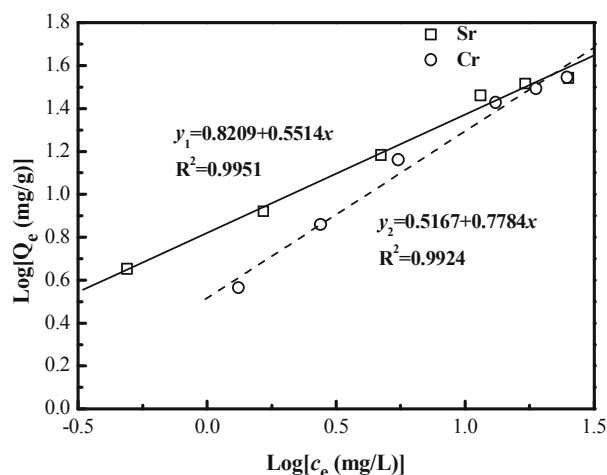


Fig. 11. Fitting curve of the Freundlich adsorption isotherm of Cr(VI) and Sr(II) onto laterite

Table 4. The parameters for Langmuir and Freundlich isotherms of Cr(VI) and Sr(II) onto laterite

Ions	Models	Parameters		
		b [$\text{L} \cdot \text{mg}^{-1}$]	Q_{\max} [$\text{mg} \cdot \text{g}^{-1}$]	R^2
Cr(VI)	Langmuir	0.046	67.57	0.9889
Sr(II)		0.155	44.05	0.9879
		k_F [$\text{mol}^{1-n} \cdot \text{L}^n \cdot \text{g}^{-1}$]	n	R^2
Cr(VI)	Freundlich	3.286	1.285	0.9924
Sr(II)		6.621	1.813	0.9951

Conclusions

1. The equilibrium batch experiment data indicate that the local laterite is a suitable material for adsorption, with a maximum uptake capacity of 7.25 mg·g⁻¹ and 8.35 mg·g⁻¹ for removal of Cr(VI) and Sr(II) from aqueous solution under given experimental conditions, respectively.
2. The adsorption equilibrium of Sr(II) is reached quickly and it is strongly dependent on pH and ionic strength, while, the ionic strength has insignificant effect on Cr(VI) adsorption.
3. Temperature was found to have a positive effect on adsorption of Sr(II) onto laterite, while, the temperature has insignificant effect on Cr(VI) adsorption.
4. The adsorption process is pseudo-second-order reaction following the Langmuir and Freundlich isotherm adsorption.

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