Enhanced Recovery of Pb^{2+} Ions from Aquatic Media by Using Polyurethane Composite as Adsorbent

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Abstract Elastomeric polyurethane (PU) and its composites (PUN and PUC) with different types of filler were prepared and investigated by differential analysis. Their ability to remove Pb^{2+} ions from aqueous solutions was studied. The results indicated that, at high concentration of Pb^{2+} ions (500 mg/L), the removal efficiency of Pb^{2+} ions by PUC is better than PUN; at low concentration of Pb^{2+} ions (125 mg/L), the difference in removals between the two is only slight, i.e., 58.36 % by PUC (0.5 g/L) and 55.11 % by PUN (0.5 g/L). Moreover, PUN exhibited a well-developed site structure, providing adsorption sites for Pb^{2+} ions; for this and for cost reasons, we decided to study Pb^{2+} ions removal ability of PUN. The results showed that the maximum adsorption capacity of Pb^{2+} ions at 125 mg/L concentration at pH 5.0, when using 0.5 g/L of PUN as adsorbent, was 142.85 mg/g. Furthermore, the equilibrium data showed that the adsorption of Pb^{2+} ions on PUN obeys a pseudo-second order kinetic model, depending on adsorbent dosage, pH, initial concentration of metal ions and contact time. From these results, it is suggested that PUN adsorbent may be appropriate for the removal of Pb^{2+} ions from wastewater.

Keywords Adsorption · Pb^{2+} ions · Nanocomposites · Composites · Polyurethanes

1 Introduction

The growing needs for water, the progress of industrial applications and the increase of human technological activity are the main causes for improvement of wastewater treatment systems, particularly when heavy metal ions exist at low concentrations. Contamination from heavy metal ions represents a major hazard to ecosystems. Lead presents a significant concern, because of its toxicity, and thus, environmental health hazard in drinking and irrigation water. At certain concentrations, it may affect human organs, causing various diseases, including chronic damage to the nervous system (Deng et al. 2010; Vukovic et al. 2011; Hajiaghababaei et al. 2011). The concentration of Pb^{2+} ions in drinking water is set by WHO at 10 $\mu\text{g/L}$ (Bektas and Kara 2004). To conform to this limit, different methods have been proposed to extract lead from aqueous solutions.

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Adsorption is one of the most commonly used methods in treatment of lead contaminated water, because it is simple and economically feasible. Several materials have been proposed as adsorbents, including carbon nanotubes (Vukovic et al. 2011; Ren et al. 2011), zeolites (Bektas and Kara 2004; Hui et al. 2005), hydrous metal oxides (Su et al. 2009; Nelson et al. 2002) and biomaterials (Martin et al. 2011; Aluwalia and Goyal 2007).

The adsorption and dispersion methods of pollutants in a polymer matrix has been given great attention in recent years due to the technological importance with respect to their processing and valuable properties (Britton et al. 1989; Aithal and Aminabhavi 1990; Harogopad and Aminabhavi 1990; Aminabhavi and Khinnavar 1993; Aminabhavi and Khinnavar 1993; Aminabhavi and Naik 1999).

Elastomeric polyurethane (PU) foams have a large surface area of porous structure, which allows them to operate as matrix materials to support different kinds of adsorbents, such as activated carbon, zeolites and hydroxyapatite, which can be used in the extraction of heavy metal ions from contaminated solutions (Jang et al. 2008; Moisés et al. 2006).

The method of preparing composite materials using polymers and adsorbents has been successful. Alhakawati and Banks (2004) prepared composites using as absorbent *Ascophyllum nodosum*, and demonstrated its potential use in the elimination of copper from aqueous solutions. Moisés et al. (2006) examined the synthesis of PU foams from various adsorbents, such as pillared clay, and tested their adsorption characteristics. A common group of clay minerals are montmorillonites. Bentonite clay is a hydrated aluminum silicate, which has a high content of montmorillonite and smaller contents of other clay minerals. It has been shown to be effective in the removal of various metal ions such as zinc, lead, nickel, copper, cobalt, uranium and cadmium from polluted solutions (Smiciklas et al. 2006; Mobasherpour et al. 2011; Corami et al. 2007). However, after adsorption of metal ions from the aqueous solution, it is difficult to separate the suspended fine solids (Choi and Jeong 2008). Therefore, to overcome this problem, the combination of bentonite with polymers in the form of polymer/clay nanocomposites has been given universal attention. This is due to the fact that they have a similar structure and properties compared to pure polymers, including the improvement in storage modulus, the decrease in thermal expansion coefficients, the reduction in gas permeability, and the improvement of the ionic conductivity as a result of the increase of filler/matrix interfacial surface area (Seo and Kim 2005). Silicon dioxide (SiO_2), also known as silica, is widespread in nature, such as sand, quartz, etc. (Iler 1979). Silica is used as an additive in food fabrication due to its broad range of properties, besides its uses in different fields, such as the reinforcement of thermoplastic and thermosetting polymers (Wang 1998). One of the silica types is chromosorb, which is diatomaceous earth, and is applied as carrier holder in GC for the stationary phase (Johns 1965).

No previous investigations have been found on using the PU matrix as a carrier for bentonite and chromosorb to study their performance as adsorbents of heavy metals from contaminated solutions. In this work, PU and its composites (PUN and PUC) with different fillers have been prepared. Their adsorbing capacity of Pb^{2+} ions from aqueous solutions was examined for various weights of adsorbents and initial Pb^{2+} ion concentrations. The effects of each adsorbent weight, initial Pb^{2+} ions concentration, and the type of filler on adsorption potential were studied, based on a pseudo-second order kinetic model. The percent removal efficiency of lead ions of the PUN composite at different pH values (2–7) in the aqueous solutions was also explained. An attempt was also made to describe the equilibrium removal behavior of PUN by the Langmuir adsorption isotherm model. Finally, one aim was to compare the adsorbent efficiency of Pb^{2+} ions removal of the elastomeric polyurethane and its composites PUN and PUC.

pouring it onto a glass dish. The previous method was repeated, using 6 % wt of bentonite instead of chromosorb, to prepare PUN. The structure of the prepared PUN is presented in Fig. 1b.

2.4 Removal of Pb^{2+} Ions by PU, PUN and PUC

The removal of Pb^{2+} ions by the prepared materials was examined by observing the change of Pb^{2+} ions concentration in the aqueous solution. The adsorption isotherms were determined by introducing PU and its composites (PUN and PUC) at different weights (0.1, 0.3, 0.5, 0.7, and 1.0 g) into 1 L of aqueous solutions at different initial Pb^{2+} ion concentrations (125–500 mg/L) at pH 5.0. The adsorption of Pb^{2+} ions by PUN was affected by pH, which was varied in the range of 2.0–7.0. The pH of the Pb^{2+} ions solution was set at the desired values by using 0.1 mol/L NaOH or 0.1 mol/L HCl. Then, a 0.5 g of PUN was added to these solutions that were shaken at room temperature for 4 h. A 0.5 g of PUN adsorbent was added to a solution of Pb^{2+} ions (125 ppm) and shaken at room temperature for 4 h, to study the effect of contact time. The residual metal concentration in the aqueous solution was measured at various time intervals. Finally, the adsorption equilibrium was studied by contacting 0.5 g of adsorbents at an initial concentration of Pb^{2+} ions solution of 125 ppm at 30 °C and pH of 5.0. The mixture was shaken for 4 h. All the experiments were carried out at room temperature and an agitation speed of 129–130 rpm for 4 h. The adsorbent was removed by filtration method.

2.5 Characterization

The atomic adsorption spectrophotometer (ICE 3000 Series AA Spectrometer–Thermo Scientific, Indonesia) was used to determine the concentration of Pb^{2+} ions in the aqueous solution at 279.5 nm analytical wavelengths. The quantity of metal ions removed by the adsorbent at equilibrium (q_e , mg/g) was determined using the following equation:

$$q_e = \frac{(C_o - C_e)V}{m} \quad (1)$$

where C_o refers to the initial concentration of metal ions in mg/L, C_e is the equilibrium metal ion concentration in mg/L, V is the volume of treated solution in mL, and m is the mass of adsorbent used in g.

The percent removal (%) of metal ion was determined using the following equation:

$$\text{Removal(\%)} = \frac{C_o - C_e}{C_o} 100 \quad (2)$$

The structures of PU, clay, chromosorb, PUN and PUC samples were characterized by using the Fourier transform infrared spectroscopy (FTIR, Shimadzu 8001, Japan). The spectrum was recorded from 4000 to 400 cm^{-1} . The surface morphologies of PU, chromosorb, PUN and PUC samples were analyzed by using a scanning electron microscope (SEM), JSM-T20 (JEOL, Tokyo, Japan). To be conductive, the sample was coated with a thin layer of gold before scanning. The incorporation of bentonite and chromosorb into PU was evaluated using XRD patterns that were recorded on PANalytical, X'pert PRO (Berlin, Germany) D500 diffractometer with a back monochromatic and a Cu anticathode.

Also, the thermal properties were studied by thermo-gravimetric analysis (TGA, SDTQ 600), where all TGA spectra were analyzed in a nitrogen atmosphere at a heating rate of 10 °C/min up to 600 °C. Transmission electron microscopy (JEOL, JEM-2100, Japan) was used to

attain a high resolution image of each clay and PUN sample and determine the diameter of their nanoparticles. The samples were set on a copper grid mesh with carbon coating for 10–12 s.

3 Results and Discussion

3.1 Characterization of Adsorbents

The synthesized PU at certain ratios of NCO/OH, clay, PUN, chromosorb and PUC were characterized by FTIR spectroscopy (Fig. 2). It is clear that the PU has a strong intensity of the bands from 900 to 1300 cm^{-1} , indicating the presence of the NCO/OH with absence of the band around 2250 cm^{-1} of the isocyanate groups ($-\text{NCO}$), referring to completing the reaction and consuming all amount of the MDI.

From the FTIR spectra of clay, chromosorb, PUN and PUC, the appearance of adsorption peaks for the PU at 3290 cm^{-1} , around 2877, 1704, 1515 and 1079 cm^{-1} correspond to the N–H stretching group, $-\text{CH}_2$ -stretching, carbonyl urethane stretching, CHN vibration and C–O stretching, respectively. Also, the spectra of PU and PUN refer to all the characteristic bands of PU staying unmoved with improvement in bands at 1704 and 1515 cm^{-1} , as a result of increase in the formation of urethane linkages in PUN. The band at 1297 cm^{-1} was for amide group that was formed between clay and the PU matrix. Also, the characteristic bands of bentonite at 3628 and 3428 cm^{-1} for stretching vibrations of hydroxyl groups, and at 1112 and 462.41 cm^{-1} correspond to Si–O stretching and bending vibration, respectively (Rayanaud et al. 2002).

The stretching vibration bands appeared at 1044.53 and 521.12 cm^{-1} , according to Si–O–Si and the Al–O groups, respectively (Rayanaud et al. 2002). The spectrum of SiO_2 (chromosorb) particles was clear in Fig. 2d, where the two strong bands appeared at 1087.65 and 787.87 cm^{-1} for stretching vibrations of asymmetric and symmetric Si–O–Si, respectively (Mohan 2009). The spectrum of chromosorb has bands at 3415 and 1628 cm^{-1} , corresponding, respectively, to the stretching and bending vibrations of OH group (Aziz and Sopyan 2009). The band, responsible for stretching vibrations of O–H, was slightly shifted to 3396 cm^{-1} in the spectrum of PUC (Fig. 2e). This was attributed to the increasing ratio of the chromosorb (50 %), showing the predomination of its spectrum over that of PU.

Fig. 2 FT-IR spectra of PU (a), clay (b), PUN (c), chromosorb (d) and PUC (e)

Thermo-gravimetric analysis was used to characterize the thermal stabilities of PU and PUN. The TGA curves are shown in Fig. 3 for PU and PUN samples. It is noticed that they are quite similar due to the low amount of filler (bentonite), although some differences can be seen. The degradation pattern of polyurethanes has two thermal degradation steps, representative of the very complex process that takes place as a result of a large number of physical and chemical phenomena (Corcuera et al. 2010).

The thermal stability of polyurethane is indicated by the equilibrium between polymerization and the decomposition of linkages that join the polymer chains. So, the first stage of degradation is attributed to the decomposition of urethane bond to produce isocyanate and alcohol groups, and also, amines, ash and carbon dioxide (Corcuera et al. 2010; Mosiewicki et al. 2009). The thermal stabilities of polyurethane and its composites were in the temperature range 276 to 363 °C, because PUN contains an organic aiding agent that takes slightly less time than PU to degrade.

At the end, after completing the degradation of the assisting agent, PUN exhibits an elevated thermal resistance compared to PU at temperatures above 615 °C. This is due to development of a barrier effect for the scattering of degradation products into the gas phase, causing a “labyrinth” effect on the dispersion of silicate layers at the nanometer scale inside the polyurethane matrix. This results in the strong interfacial interaction between the organoclay layers and polyurethane chains leading to a restricted effect on polyurethane chains (Dimitry et al. 2011). It is obvious that the degradation steps are the same for PU and PUN, but for PUC with 50 % wt chromosorb higher values were exhibited (Fig. 3c). The thermal stability of polyurethane composite PUC was in the temperature range 270 to 765 °C, and the residue was about 83 % at higher temperature (1000 °C).

It was found that the thermal stabilization is less efficient at higher inorganic filler content (7 % wt), which may be attributed to less optimal platelet dispersion (steric hindrance) (Dimitry et al. 2010). On the other hand, the stabilizing effect of the chromosorb filler may be attributed to more optimal platelet dispersion, indicating that these structural –OH groups, which exist on the surface of the silicate layers, could react more with the –NCO groups of the polymer chains. This may be regarded as the increasing ratio of the chromosorb (50 %), where this is clear by the predomination of chromosorb spectrum over PU. So, the degradation has mainly occurred for segments of polyurethane and is nearly rare for chromosorb to give a PUC residue 83 % at high temperature (1000 °C).

Fig. 3 TGA of PU, PUN and PUC

XRD spectra of PU, clay, PUN, chromosorb and PUC are presented in Fig. 4. The XRD characterization is commonly based on the observation of the shifting position of the diffraction peak of the nanoclay powder intercalated in the polymer matrix (Dimitry et al. 2011). It is shown that the reflections belong to 001 plane, natural bentonite clays (d -spacing = 1.24 nm, $2\theta=7.12^\circ$) (Fig. 4b).

The comparative curves obtained for the nanocomposite PUN and clay represent an amorphous halo in the PUN sample. Three diffraction peaks in the range $2\theta=18\text{--}23^\circ$, can be noticed in Fig. 4a–c. The incorporation of clay reduces the peak intensity of clay, and also a shift by 2θ is seen in Fig. 4c for PUN. The XRD of PUN shows that the diffraction peak of PUN appears at $2\theta=21.3^\circ$, when compared to $2\theta=18.48^\circ$ for PU, suggesting that the organoclay is highly intercalated. The crystalline peak of chromosorb at $2\theta=22.2^\circ$ has a slight shift in PUC, as shown in Fig. 4d and e. This may be attributed to joining of chromosorb with PU, i.e., the crystal structure of chromosorb is kept in PUC composite. Though there was not change in the crystallite structure of chromosorb, it was possible to evaluate the influence of chromosorb domains in the crystalline structure of PU.

The SEM analysis (Fig. 5b) shows the morphology of PUN. It appears having a rough surface, as a result of the presence of the bentonite particles inside the structure of the polymer. But, Fig. 5a shows that PU has a smooth and dense surface. The morphology of PUC indicates that the polymer can be used as cover in silica materials to prevent them from aggregating (Fig. 5d), but aggregation has occurred in the morphology of chromosorb (Fig. 5c).

By using TEM analysis, the particle diameter of clay, PUN and PUC samples was determined and is shown in Fig. 6a and b. The lattice fringe of the organoclay silicate layers was observed in the PU matrix; it was noticed that, at 6 % wt filler loading, the clay layers were nearly adjoining to each other with some interlayer spacing larger than the one of raw bentonite. The particle size of bentonite is 10.80 to 26.70 nm and that of PUN is 14.47 nm; this is an evidence that this organoclay is intercalated in the PU matrix. At higher organoclay content of 6 % wt bentonite, the layered filler is arranged in intercalated layers. In this case, the effective entry of PU molecules between the organically modified inter-lamellar spacing could not be achieved to cause an exfoliation of the silicate layers in PU.

Moreover, agglomeration of PUN is observed and can be explained by the increase in the amount of clay to 6 % wt. The tendency of nanoparticles to agglomerate further increases at higher clay % wt, as reported in other studies (Chiscan et al. 2012). So, the transmission electron micrographs confirm the XRD results. Figure 6c shows that the particle size of PUC is around 0.2 to 0.47 μm , and the increase in agglomeration of PUC particles compared to PUN, may be attributed to the increase of the clay amount to 50 %.

Fig. 4 X-ray diffraction (XRD) of PU (a), clay (b), PUN (c), chromosorb (d) and PUC (e)

Fig. 5 SEM pattern of PU (a), PUN (b), chromosorb (c) and PUC (d)

However, having a single particle or very improved dispersion of silica within the polymeric matrix is still a challenge due to aggregation, since aggregation normally occurs as a result of the incompatibility between silica particle surface chemistry and polymer matrix. In addition, this aggregation can be attributed to the formation of hydrogen bonds due to the presence of silanol groups on adjacent particles. This is because silica particles contain a high concentration of -OH groups due to silanol functions. So, these bonds hold the particles together even under the best mixing conditions, if stronger interactions between the filler and the polymer are not present (Sadhan and Sachin 2001). In addition to the fact that SiO_2 is used as a low cost filler, previous reports and results also have shown an enhancement in the thermal properties of different hybrid films that were fabricated using SiO_2 as filler (Giannelis 1996; Al-Sagheer and Muslim 2010).

Fig. 6 TEM of: (a) Clay (bentonite), (b) PUN and (c) PUC

3.2 Effect of Type, Particle Size and Amount of Filler of PU Composite on Pb^{2+} Ions Adsorption

The content and particle size of bentonite and chromosorb in PU composite may affect the removal of the Pb^{2+} ions in the aqueous solution. Therefore, the removal process of Pb^{2+} ions from the aqueous solution containing an initial Pb^{2+} ions concentration of 125 mg/L at pH 5.0, using different weights (0.1 to 1.0 g/L) of PU, PUN and PUC adsorbents, was investigated.

As shown in Fig. 7, the removal efficiency (Eq. 2) of metal ions increases with the increase in filler content in this order: PU (44 %) < PUN (60 %) < PUC (63.76 %). Generally, an appropriate addition of clay particles may improve the adsorption. The optimum removal of Pb^{2+} ions by PUN with bentonite content 6 % wt is slightly less than that of PUC with 50 % wt chromosorb, as seen in Fig. 7b–c. This is attributed to the provision of more adsorption sites by the nanosized particles of PUN with low bentonite content for adsorption of Pb^{2+} ions from aqueous solutions.

Fig. 7 The effect of adsorbent dosage of PU (a), PU + clay (b), and PU + chromosorb (c) on removal efficiency (%) of Pb^{2+} ions in aqueous solution at concentrations of 125, 250 and 500 mg/L at pH = 5.0

However, the adsorption sites of PUC were nearly the same as of PUN, where the particles at the nanosize provide a larger area with more adsorption sites than at the micro-size. Furthermore, the addition of 6 % wt of bentonite can reduce the production cost of the adsorbents, but the addition of 50 % wt of chromosorb is not that economic, although it improved Pb^{2+} ion adsorption. This result indicates that PUN containing 6 % wt of bentonite is the optimized system.

3.3 Effect of Adsorbent Dosage on Pb^{2+} Ion Adsorption

The adsorption of Pb^{2+} ions on PU, PUN and PUC was studied for different adsorbent dosages, varying from 0.1 to 1.0 g/L in 125, 250 and 500 mg/L solutions of lead ions at pH 5.0. As shown in Fig. 7a–c, the highest efficiency of lead ion removal is obtained for 1.0 g/L weight of adsorbents PU and PUN. Though the adsorption efficiency was 96 %, it was noticed that the increase in adsorption efficiency of PUN and PUC at dosages between 0.5 and 1.0 g/L was very small. This was attributed to the increase in filler ratio of the adsorbents, leading to improvement in the absorbance performance of the polymer at a certain adsorbent dosage.

From the previous results, it may be concluded that an economic amount of PUN is about 0.5 g/L in solutions for use in the treatment of contaminated water with Pb^{2+} ion concentrations of 125, 250 and 500 mg/L.

Fig. 8 The effect of pH on the adsorbed amount (q_e) of Pb^{2+} ions by 0.5 g/L of PUN at 125 mg/L concentration of lead solution, after 4 h of contact time

3.4 Effect of Initial Lead Ion Concentration on Pb^{2+} Ion Adsorption

The removal efficiency of PU, PUN and PUC adsorbents for three different initial Pb^{2+} ion concentrations of 125, 250 and 500 mg/L was studied at solutions adjusted to pH = 5.0. It was found that the removal efficiency of Pb^{2+} ions was higher for higher initial concentrations of Pb^{2+} ion (Fig. 7a–c).

It is clear from Fig. 7a–c that the maximum removal efficiency of Pb^{2+} ion by PU, PUN and PUC adsorbents (1.0 g/L), in Pb^{2+} ion solutions at 500 mg/L initial concentration, was 62.21, 64.46 and 96 %, respectively, while at 125 mg/L concentration, the respective removal efficiencies were approximately 44, 60 and 63.76 %. It is also shown, that the maximum removal of lead ions, at 500 mg/L initial concentration, was achieved by PUC. However, the difference of removal efficiencies of Pb^{2+} ion by PU, PUN and PUC adsorbents for initial concentrations of 250 and 125 mg/L was only slight. Therefore, in all subsequent experiments, we used Pb^{2+} ion solutions of 125 mg/L concentration, at pH 5.0, using 0.5 g/L of PUN adsorbent, at 30 °C (Figs. 8, 9 and 10).

Fig. 9 The effect of time on removal efficiency (%) of Pb^{2+} ions by 0.5 g/L of PUN at 125 mg/L concentration of lead solution, at pH = 5.0

Fig. 10 The representation of lead ions removal by 0.5 g/L of PUN at 125 mg/L concentration of lead solution, at pH = 5.0 using Langmuir isotherm model

3.5 Effect of pH on Removal Efficiency (%) of Pb^{2+} Ions by PUN

The adsorption ability of Pb^{2+} ions was also studied at 125 mg/L initial concentration by using 0.5 g/L of PUN adsorbent at pH varied in the range 2.0 to 7.0 after 4 h (Fig. 8). The removal efficiency (%) was found to increase with increasing pH and reach a peak of 137.7 mg/g at pH = 5.0. The removal efficiency (%) started decreasing for pH > 5.0, but was kept nearly constant in the pH range 6.0 to 7.0 at around 120 ± 1 mg/g. These results indicate that the adsorption of Pb^{2+} ions is significantly affected by pH, as Pb^{2+} ion solubility and the ionization state of the functional groups of PUN adsorbent are affected by the pH of the Pb^{2+} ion solution. At pH = 6.0, the reduced removal efficiency (%) of Pb^{2+} ions may result from precipitation of metal ions in the form of their hydroxides (Afkhamia et al. 2010). Therefore, additional adsorption experiments were carried out at optimum pH = 5.0, where q_{max} was 137.7 mg/g.

3.6 Effect of Contact Time on the Removal Efficiency of Lead Ions by PUN

The adsorption kinetics of an adsorbent for a given initial adsorbate concentration were controlled by the contact time. The effect of contact time on adsorption efficiency of Pb^{2+} onto PUN was investigated at 125 mg/L concentration of Pb^{2+} ions, for 4 h, as shown in Fig. 9. The removal efficiency of Pb^{2+} ions increased sharply in the first 30 min of contact time. This is probably due to the saturation of adsorption sites of PUN and reached the system to the equilibrium point at this time.

Table 1 Adsorption capacities of Pb^{2+} ions by various adsorbents

Adsorbents	q max (mg/g)	Reference
Activated carbon	31.20	[44]
Polyacrylamide/bentonite composite	33.12	[45]
PU nanocomposite with 6 % bentonite	142.85	this work
HAp (50 %wt) /PU composite foam	150.00	[46]

3.7 Adsorption Isotherm of the Lead Ions by PUN

The adsorption isotherm of the lead ions by PUN was studied at pH = 5.0, where the removal of Pb²⁺ ions from the aqueous solution was controlled by the ion exchange mechanism. The Langmuir adsorption isotherm model expressed quantitatively the relationship between the amount of adsorption and the residual solute concentration, as follows (Langmuir 1946):

$$\frac{C_e}{q_e} = \frac{1}{K_e q_{\max}} + \frac{C_e}{q_{\max}} \quad (3)$$

where C_e (mg/L), q_e (mg/g), K_e and $q_{\max}$ refer to the equilibrium concentration, the ratio of adsorbed mass per adsorbent mass (mg/L), the Langmuir equilibrium constant (L/mg), and the maximum ratio of adsorbed mass per adsorbent mass (mg/L) with respect to complete monolayer coverage, respectively. The fit of Eq. (3) to the experimental data is acceptable, as shown in Fig. 10, yielding $q_{\max} = 142.85$ mg/g and $K_e = 0.12$ L/mg. When the $q_{\max}$ value of PUN is compared to that of other adsorbents (Table 1) (Machida et al. 2005; Ulusoy and Simsek 2005; Suk et al. 2008), the adsorption capability of Pb²⁺ ions by PUN is found to be comparable or even superior. From these results, it is deduced that PUN is an efficient adsorbent of lead ions.

4 Conclusions

The goal of this work was to examine the removal efficiency of Pb²⁺ ions from aqueous solutions at pH values 2.0 to 7.0 for a 4 h contact time, by the prepared polymers PU, PUN and PUC. The composites PUN and PUC provide more sites for adsorption of Pb²⁺ ions and improve the removal efficiency of Pb²⁺ ions. In spite of the fact that PUC provides more sites for adsorption than PUN based on comparison to their ratios (50 and 6 %, respectively), and their size particles, PUN showed a reasonable efficiency with respect to particles size and the amount of its filler content. The removal efficiency of Pb²⁺ ions was found to depend on the pH value of the aqueous solutions and reached a maximum value of 137.7 mg/g, at pH 5.0. The adsorption isotherm of the Pb²⁺ ions by PUN can be described by the Langmuir isotherm model. It was revealed that the maximum adsorption capacity of PUN was 142.85 mg/g, indicating that PUN has an effective absorbing capacity of Pb²⁺ ions at pH varying from 5.0–6.0, making it possibly useful in wastewater treatment. Furthermore, the use of chromosorb as a filler at micro-size to form PUC is attractive, since this composite has a good ability to adsorb Pb²⁺ ions. However, the disadvantage of this composite is that it contains 50 % wt of filler, and so, it is not an economical adsorbent to use.

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