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Removal of arsenic from ammoniacal etching waste liquor by 3-(2-aminoethylamino)propyltrimethoxysilane functionalized silica gel sorbent

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ABSTRACT

3-(2-Aminoethylamino)propyltrimethoxysilane (AAPTS) functionalized silica gel (AAPTS/SiO_2) was synthesized by a sol–gel process and was used for the arsenic removal from ammoniacal etching waste liquor which was oxidized by H_2O_2. The AAPTS/SiO_2 sorbent reached absorption saturation at 20 min and had a substantial binding capacity in the range of pH 4.7–10.2. The maximum static adsorption capacity of AAPTS/SiO_2 sorbent for arsenic was 16.1 mg g^{-1}. Equilibrium data fitted perfectly with Langmuir isotherm model compared to Freundlich isotherm model. The removal rate of arsenic by AAPTS/SiO_2 sorbent was 95.4% at the optimal conditions from ammoniacal etching waste liquor. Results showed that AAPTS/SiO_2 sorbent could be used for the arsenic removal from ammoniacal etching waste liquor.

Keywords: Removal; Arsenic; 3-(2-Aminoethylamino)propyltrimethoxysilane; Silica gel; Etching waste liquor

1. Introduction

Inorganic arsenic commonly occur in two forms namely As(III), which exists mostly as neutral arsenious acid, and As(V), which exists mainly as negatively charged oxyanions of arsenic acid [1]. As(III) is 25–60 times as toxic as As(V) [2].

Over the past 10 years in China, the field of printed circuit board production has grown sharply [3]. Alkaline ammoniacal ammonium chloride etchant is widely used to etch copper during the manufacture of printed circuit board [4]. The etching waste liquor contains large amounts of copper and small amounts of other heavy metals (e.g. Pb, Cd, As) [3]. Disposal of etching waste liquor involves a loss of resources and is usually environmentally unacceptable. Some saleable copper products (e.g. elemental copper, copper sulfate) have been obtained from etching waste liquor [4–7].

The removal of arsenic from ammoniacal etching waste liquor was essential prior to the preparation of tribasic copper chloride feed additive due to its high concentrations in etching waste liquor and its well known toxicity. Most arsenic removal technologies are more effective in removing As(V) than As(III), since As(V) is normally present as an anion in the medium-pH range while As(III) exists as uncharged molecules below pH 9.2 in water [1,8,9]. Therefore, many treatment systems include an oxidation step to convert As (III) to As(V) prior to the process of arsenic removal [1,10,11]. Hydrogen peroxide is an effective oxidant for the arsenic removal [8,12,13].

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3-(2-Aminoethylamino)propyltrimethoxysilane (AA PTS) is a kind of silylating and coupling reagent which is used to modify the surface of inorganic materials and organic polymer. Chen et al. [9] have reported that AAPTS onto the surface of the mesoporous silica as sorbent can selectively adsorb the As(V) and be used for the determination of arsenic speciation in aqueous solution. Zheng and Hu [14] have reported that AAPTS modified silica can preconcentrate As(V). In this study, we are presenting a synthesized AAPTS-functionalized silica gel (AAPTS/SiO_2) as a sorbent for the removal of arsenic from ammoniacal etching waste liquor treated with H_2O_2. The adsorption behaviors and maximum static adsorption capacity of AAPTS/SiO_2 sorbent for As(V) were investigated. The effect of pH and adsorption time on the adsorption capacity of AAPTS/SiO_2 sorbent had been studied. The influence of usage of H_2O_2 and AAPTS/SiO_2 sorbent on the removal rates of arsenic in ammoniacal etching waste liquor was tested. The AAPTS/SiO_2 was applied to the removal of arsenic from ammoniacal etching waste liquor at the optimal conditions.

2. Experimental

2.1. Synthesis and characterization of AAPTS/SiO_2 sorbent

Eight grams of mesoporous amorphous silica gel (80–120 mesh, Qingdao Ocean Chemical Co., Qingdao, China) was activated by refluxing in 33% methanesulfonic acid solution for 24 h and then washed thoroughly with the deionized water and dried under vacuum at 70℃ for 8 h before undergoing chemical surface modification. After refluxing the activated silica gel (6 g) and 4 mL of AAPTS (Sigma) were mixed in 80 mL of dry toluene for 24 h under stirring and heating. The solid materials (AAPTS/SiO_2) were filtered off and washed with ethanol and then dried under vacuum at 60℃ overnight [14]. The IR spectra of the AAPTS/SiO_2 sorbents were recorded by the KBr pellets method using a Spectrum One spectrometer (Perkin Elmer, USA) in 4,000–400 cm^{-1} region, with a resolution of 1 cm^{-1}. The surface morphology of the AAPTS/SiO_2 sorbents was examined using a scanning electron microscopy (SEM) (SSX-550, Shimadzu, Japan) at the desired magnification operating at 30 kV. The surface area and pore size distributions were determined from adsorption–desorption isotherms of nitrogen at 77 K (ASAP 2010C, Micromeritics, USA). Specific surface areas were estimated using Brunauer–Emmett–Teller (BET) equation. The pH of the point of zero charge (pH_{PZC}) was measured using the pH drift method [15]. The pH of the solution was adjusted using 0.01 M sodium hydroxide or hydrochloric acid and nitrogen was bubbled through the solution at 25℃ to remove dissolved carbon dioxide. Fifty milligrams of AAPTS/SiO_2 adsorbent was added to 50 mL of the solution and the suspension was stirred for 24 h to reach equilibrium. After stabilization, the final pH was recorded. The content of silanol groups on the surface of silica was measured by thermogravimetry method using a thermogravimetric analyzer (HCT-2, Beijing Scientific Instrument Factory, China) varying from 50 to 800℃ at a heating rate of 10℃ min^{-1} in argon flow with an initial mass of approximately 20.0 mg of solid [16,17]. The content of silanol groups was calculated from the second mass loss step from 250 to 800℃ [16,17].

2.2. Adsorption and desorption tests of AAPTS/SiO_2 sorbent

Adsorption of arsenic from aqueous solutions was investigated in batch experiments. The static adsorption rate of AAPTS/SiO_2 sorbent were studied. The effect of pH on the adsorption capacity of the AAPTS/SiO_2 sorbent was investigated with 20 mL of 10 mg L^{-1} As(V) solutions in the pH range of pH 2.7–10.2. To measure the maximum adsorption capacity, AAPTS/SiO_2 sorbents were equilibrated with 20 mL of the various concentrations of As(V) solutions (1–50 mg L^{-1}) at pH 7.5 and after that, this pH was applied for all the experiments. The suspensions were brought to the desired pH by adding sodium hydroxide and nitric acid. The ratio of solid to solution was kept constant at 0.5 g L^{-1}.

Several stripping agents such as EDTA, HNO_3, and HCl, were used to desorb the As(V) from the imprinted sorbent. The AAPTS/SiO_2 sorbents was placed in 5 mL of desorption medium and stirred continuously at a stirring rate of 600 rpm from 1 to 4 h at room temperature. The desorption ratio was calculated from the amount of AAPTS/SiO_2 sorbent adsorbed and the final As(V) concentration in the desorption medium. To test the reusability of the AAPTS/SiO_2 sorbent, the As(V) ions adsorption–desorption procedure was repeated five times by using the same sorbent.

In all above batch experiments, the mixtures were magnetically stirred at room temperature, and the concentrations of As(V) in the aqueous phases after desired treatment periods were centrifugally separated and measured. An atomic absorption spectrometer coupled to hydride generation (HG-AAS, PE, USA) was used to measure the concentration of As in aqueous solution after appropriate dilutions for the study of the As uptake of the prepared new sorbent. All the reagents were of analytical grade and purchased from

Sinopharm Chemical Reagent Co., Ltd., Shanghai, China. The stock solution of arsenic (1,000 mg L^{-1}) was purchased from the National Research Center for Standard Materials (Beijing, China). The working solutions were prepared by series dilution of the stock solutions immediately prior to their use. The solutions were prepared weekly and stored in a refrigerator.

2.3. Removal of arsenic from ammoniacal etching waste liquor

The composition of ammoniacal etching waste liquor was shown in Table 1. The ammoniacal etching waste liquor contained large amounts of ammonia, chloride, and copper. The concentrations of As(III) and As(V) were roughly equal.

It is necessary for the oxidation of As(III) due to As(III) mostly existed in the form of neutral H_3AsO_3 species below pH 9.2. The H_2O_2 solution is often used to oxidize As(III) and its usage has to be optimized. The different masses of 30% H_2O_2 solutions (0.5, 1, 2.2, 3.5, 5, 7 and 10 mL) were added to 20 mL of etching waste liquor (Shenzhen Jiepuli Electron Science and Technology Co., Ltd., Shenzhen, China) under stirring for 1 h at room temperature, and then 0.1 g of AAPTS/SiO_2 sorbent was added into 20 mL of etching waste liquor and stirred for 0.5 h at room temperature. The deposition was removed by filtration. The amounts of As(III), As(V) and total arsenic in the purified etching waste liquor were determined by an atomic absorption spectrometer coupled to hydride generation (Perkin Elmer, USA) and the removal rates were calculated.

3. Results

3.1. Synthesis of AAPTS/SiO$_2$ sorbent

As known, silica gel is an amorphous inorganic polymer with siloxane groups (Si–O–Si) in the bulk and silanol groups (Si–OH) on its surface. The silanol groups are responsible for chemical modifications and facilitate the introduction of the organic groups which covalently bind to the silica surface. Because commercial silica gel possesses a low concentration of surface silanol groups suitable for modification, the activation of silica gel surface is necessary. In this work 33% of methanesulfonic acid solution was used for the activation of the silica gel because of its strong catalytic action; high boiling point, which prevents it from contaminating the air; and its ability will be used repeatedly [18]. The contents of silanol groups on the surface of silica before and after activation were 0.56 and 3.2 wt.%, respectively. It showed that the surface of silica gel had been activated. Then, the activated silica gel surface was grafted with AAPTS. After the remnant AAPTS were removed by ethanol, the AAPTS/SiO_2 sorbent was formed (Fig. 1).

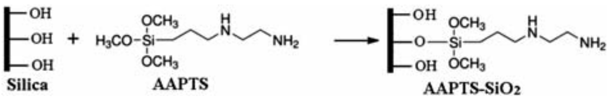

Fig. 1. Preparation procedure of AAPTS/SiO_2 sorbent.

3.2. Characterization of AAPTS/SiO$_2$ sorbent

In order to confirm the presence of AAPTS in the functionalized silica gel sorbents, the FTIR spectra of silica gel and AAPTS/SiO_2 sorbents are shown in Fig. 2. The presence of NH_2 groups is reflected by vibration bands at 3,489 and 1,535 cm^{-1}. The absorption band at 2,872 cm^{-1} is assigned to vibrations of CH_2 groups. The presence of OH groups is reflected by vibration bands at 3,430 cm^{-1} and at 1,635 cm^{-1} due to the surface silanol groups

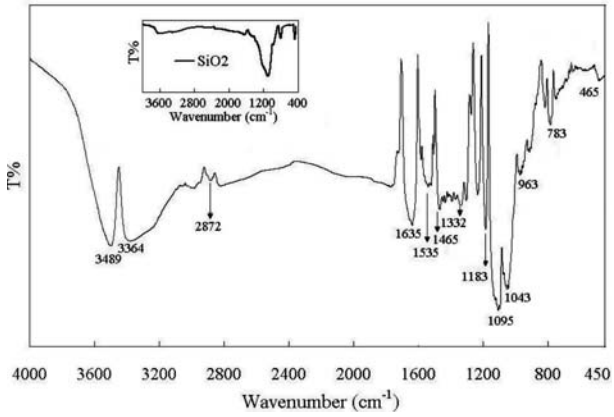

Fig. 2. IR spectra of AAPTS/SiO_2 sorbent.

Table 1
The composition of ammoniacal etching waste liquor

Composition	Pb (mg L^{-1})	As(III) (mg L^{-1})	As(V) (mg L^{-1})	Cu^{2+} (g L^{-1})	NH_3 (g L^{-1})	Cl^- (g L^{-1})	d^{25} (g L^{-1})	pH
Contents	127.2	39.15	47.34	124.1	136.2	180.1	1.20	8.5

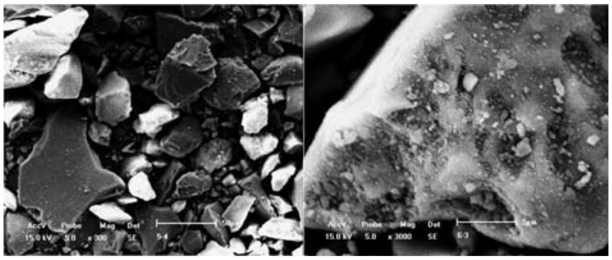

Fig. 3. SEM of AAPTS/SiO_2 sorbent.

with hydrogen bond and the remaining adsorbed water molecules [19]. A broad peak is noted at 1,095 cm^{-1}, due to the siloxane vibrations of $(SiO)_n$. The broad peak has been shifted to lower wavenumbers at 1,043 cm^{-1}, while the shoulder is more clearly observed at 1,183 cm^{-1} due to the vibration $\delta s(Si–CH_2)$ [20]. The band at 963 cm^{-1} is assigned to Si–OH stretching. Other bands at 783 and 465 cm^{-1} are assigned to Si–O–Si stretching and Si–O–Si bending, respectively [21]. The bands at 1,465 and 1,320 cm^{-1} correspond to $\delta(N–CH_2)$ and CH_2 groups in phase twist [22]. All these features indicate that AAPTS has been successfully immobilized on the surface of silica gel.

AAPTS/SiO_2 sorbents were characterized using SEM in order to know the surface morphological image. The SEM images of the AAPTS/SiO_2 sorbents are shown in Fig. 3. The chemically immobilized surface with AAPTS suggested a charge in the structure, due to the attached silylating agent. The rough surfaces of AAPTS/SiO_2 sorbents were responsible for the high surface area and high As(V) adsorption.

The results of nitrogen sorption isotherms showed that AAPTS/SiO_2 sorbents had a BET surface area of 139 $m^2 g^{-1}$. The charge of the surface of AAPTS/SiO_2 adsorbent during adsorption was determined by the pH of the solution. The pH_{PZC} determined in this manner was 9.4 ± 0.5. At $pH < pH_{PZC}$, AAPTS/SiO_2 surface was positively charged whereas at $pH > pH_{PZC}$ AAPTS/SiO_2 surface was negatively charged.

3.3. Adsorption of AAPTS/SiO_2 sorbent

3.3.1. Effects of pH

The effect of pH on the adsorption capacity of AAPTS/SiO_2 sorbent and commercial silica for As(V) was tested by varying the pH from 2.7 to 10.2 (Fig. 4). As can be seen, a significant difference was observed between AAPTS/SiO_2 sorbent and commercial silica for the adsorption capacity of As(V). The adsorption capacity of commercial silica was very low in the whole tested pH range. It was because that only physical adsorption driving forces between As(V) and commercial silica were present, resulting in less adsorption capacity. For AAPTS/SiO_2 sorbent, there is a low affinity in acidic concentration at pH 2.7 and a high affinity at pH $\geq$3.7. At pH 2.7, the adsorption capacity decreased because partly As(V) were neutral in charge according to the p*K*a values of As(V) ($pK_{a1} = 2.3$, $pK_{a2} = 6.97$ and $pK_{a3} = 11.53$) [23]. After pH 3.7, the adsorption capacity increased and remained relatively constant. It was because that As(V) can be adsorbed by AAPTS/SiO_2 sorbent through electrostatic effect [9]. The As(V) compounds are negatively charged, while $-NH_3^+$ group is the main existing form of AAPTS when the pH value is below 9, based on the $pKa = 9.3$ for $NH_3{\cdot}H_2O$ [9].

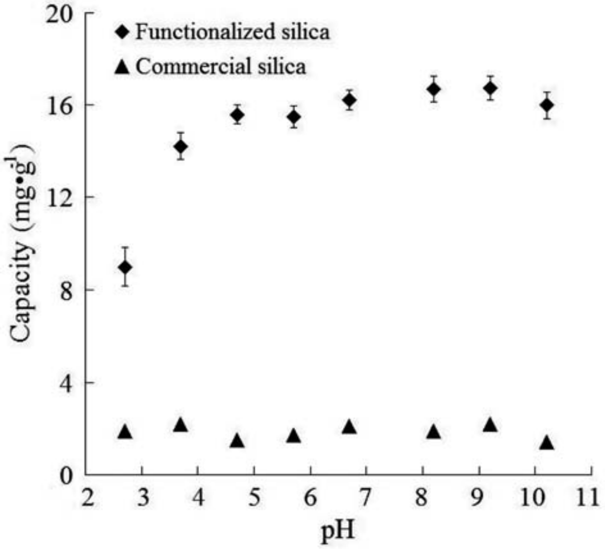

Fig. 4. Effect of pH on the adsorption capacity of AAPTS/SiO_2 for As(V): The pH range of As(V) solution = 2.7–10.2, concentration of As(V) = 10 mg L^{-1}, reaction time = 30 min, dosage = 5 g L^{-1}, temperature = 25℃.

3.3.2. Kinetic curve of adsorption rate

Many applications, such as wastewater treatment and metal purification, need rapid adsorption rate and short contact time. The adsorption rate is an important parameter used to image the adsorption process. Fig. 5 shows the time dependence of the adsorption capacity of AAPTS/SiO_2 sorbent for As(V). As seen here, the adsorption capacity of As(V) ions increased with the time during the first 30 min and then a saturation value was reached. It was reasonable to assume that this fast adsorption process was due to strong chelation of AAPTS/SiO_2 sorbent and its smaller diffusion barrier [18].

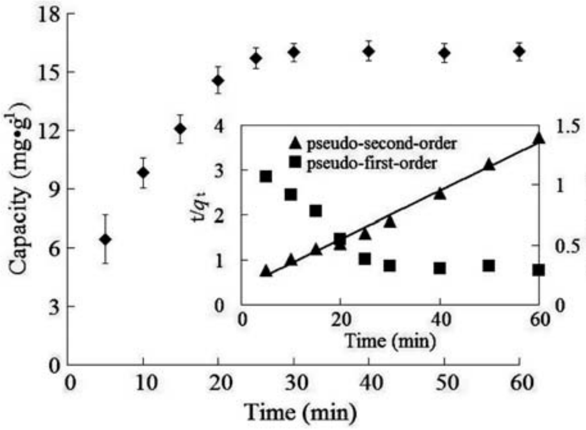

Fig. 5. Adsorption rate of AAPTS/SiO_2 sorbent for As(V) ions: Range of reaction time = 5–60 min, concentration of As(V) = 10 mg L^{-1}, pH = 7.5, dosage = 5 g L^{-1}, temperature = 25℃.

Two different kinetic models (the pseudo-first-order and pseudo-second-order kinetic models) were used to fit the experimental data.

The linear expression of pseudo-first-order kinetic model for the adsorption of solid/liquid systems is given as [23]:

$$\lg(q_{\mathrm{eq}} - q_t) = \lg q_{\mathrm{eq}} - k_1 t/2.303 \qquad (1)$$

where q_t is the adsorption capacity at time t (mg g^{-1}) and k_1 (min^{-1}) is the rate constant of the pseudo-first-order adsorption. The rate constant, k_1 and correlation coefficients were calculated from the linear plots of lg ($q_{\mathrm{eq}} - q_t$) vs. t and are listed in Table 2. However, linearity of the plots did not necessarily assure the pseudo-first-order mechanism. There was a large deviation between the calculated values and the experimental values of adsorption capacity. The pseudo-first-order kinetics was therefore less likely to explain the rate processes.

The kinetic data were further analyzed using Ho's pseudo-second-order kinetics model. This model is based on the assumption that the sorption follows second order chemisorptions [24]. It can be represented in a linear expression as Eq. (2)

$$t/q_t = 1/k_2 q_{\mathrm{eq}}^2 + t/q_{\mathrm{eq}} \qquad (2)$$

where k_2 (g $\mathrm{mg}^{-1}\,\mathrm{min}^{-1}$) is the rate constant of the pseudo-second-order adsorption. The rate constant k_2, the q_{eq} value, and the corresponding linear regression correlation coefficient r^2 were calculated from the linear plots of t/q_t against t and are given in Table 2. The values of q_{eq} (cal), and k_2 for the AAPTS/SiO_2 sorbents were 17.0 mg g^{-1} and 2.23×10^{-2} g $\mathrm{mg}^{-1}\,\mathrm{min}^{-1}$, respectively. The straight lines with extremely high correlation coefficients ($r^2 > 0.99$) were obtained. In addition, the calculated q_{eq} values also agreed with the experimental data in the case of pseudo-second-order kinetics. These results suggested that the adsorption data of the AAPTS/SiO_2 sorbents were well represented by pseudo-second-order kinetics model.

3.3.3. Adsorption capacity

The adsorption capacity is an important factor to evaluate the AAPTS/SiO_2 sorbent. Fig. 6 shows the initial concentration of As(V) dependence of the adsorbed

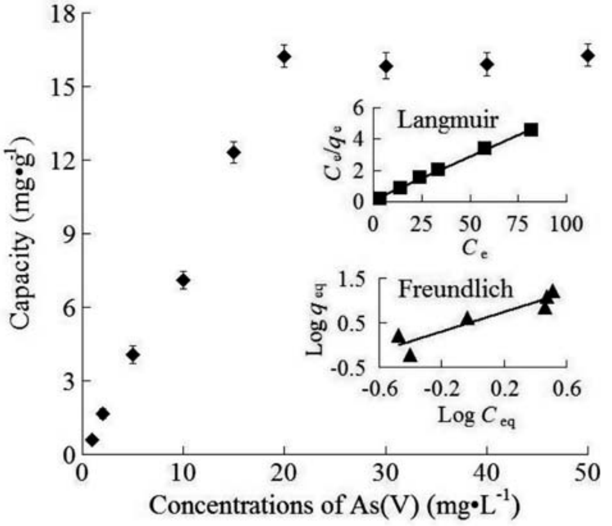

Fig. 6. Adsorption capacity of AAPTS/SiO_2 sorbent for As(V): Concentrations range of As(V) solution = 1–50 mg L^{-1}, reaction time = 30 min, pH = 7.5, dosage = 5 g L^{-1}, temperature = 25℃.

Table 2
Kinetic parameters of arsenic(V) adsorption on AAPTS/SiO_2 sorbent

q_{eq} (exp) (mg g^{-1})	Pseudo-first-order model			Pseudo-second-order model		
	k_1 (min^{-1})	q_{eq} (cal) (mg g^{-1})	r^2	k_2 ($\times 10^{-3}$ g $\mathrm{mg}^{-1}\,\mathrm{min}^{-1}$)	q_{eq} (cal) (mg g^{-1})	r^2
16.1	0.04	12.2	0.6725	22.3	17.0	0.9903

amount of AAPTS/SiO_2 sorbent. The values of adsorption capacity increased with the increase of the initial concentrations of As(V) solution in the range from 1 to 20 mg L^{-1}, then the adsorption capacity reached a plateau. The static adsorption capacity (16.1 mg g^{-1}) of the AAPTS/SiO_2 sorbent for As(V) was obtained.

The Langmuir model assumes monolayer coverage of adsorbate over a homogeneous adsorbent surface. The binding sites are also assumed to be energetically equivalent and distant from each other, so there are no interactions of molecules adsorbed on adjacent sites. The Langmuir model can be described as Eq. (3)

$$q_e = q_{\max} b C_e / (1 + b C_e) \tag{3}$$

where q_e is the amount of adsorbed As(V) in the adsorbent (mg g^{-1}), C_e is the equilibrium ion concentration in solution (mg L^{-1}), b is the Langmuir constant, and $q_{\max}$ is the maximum adsorption capacity (mg g^{-1}) [25–28].

The Freundlich expression is an exponential equation that describes reversible adsorption and is not restricted to the formation of the monolayer. This empirical equation takes the form Eq. (4)

$$q_{eq} = K_F C_{eq}^{1/n} \tag{4}$$

where K_F and n are the Freundlich constants; C_{eq} is the equilibrium ion concentration in solution (mg mL^{-1}) [25–28].

Table 3 shows the constants of the Langmuir and Freundlich isotherms. According to the correlation coefficients of isotherms, the Langmuir adsorption model is more favorable than the Freundlich model, while a low difference of $q_{\max}$ values between the experiment (16.1 mg g^{-1}) and calculation (18.1 mg g^{-1}) was observed, indicating a good Langmuir isotherms fit to the experimental data.

3.3.4. Desorption and repeated use

The regeneration of the commercial AAPTS/SiO_2 sorbent is likely to be a key factor in improving wastewater process economics. In this study, desorption of the adsorbed As(V) ions from AAPTS/SiO_2 sorbent was also studied in batch experimental set-ups (Table 4). The desorption time was found to be 4 h. Desorption ratios were very high (up to 95%). Compared with HNO_3, HCl is cheap. Thus, 3 mol L^{-1} HCl solution was used as a desorption agent. When HCl is used as a desorption agent, the As(V) ions were released from AAPTS/SiO_2 sorbent into desorption medium. It was most possibly due to complete protonation of donating nitrogen atoms of binding sites.

Table 3
Adsorption isotherm constants for the adsorption of arsenic(V) onto AAPTS/SiO_2 sorbent

Langmuir adsorption isotherm	Freundlich adsorption isotherm
$q_{\max}$ = 18.1 mg g^{-1}	K_F = 0.403
b = 0.441	n = 1.287
r^2 = 0.9972	r^2 = 0.861

Table 4
Effects of stripping agents on As(V) desorption

Stripping agents	Time (h)	Recovery (%)
0.1 mol L^{-1} EDTA	2	32.8
1 mol L^{-1} HNO_3	2	60.1
3 mol L^{-1} HNO_3	2	85.7
3 mol L^{-1} HNO_3	4	95.8
1 mol L^{-1} HCl	2	55.4
3 mol L^{-1} HCl	2	83.7
3 mol L^{-1} HCl	3	94.2
3 mol L^{-1} HCl	4	95.1

Table 5
Five stripping cycles of AAPTS/SiO_2 sorbent

Stripping cycle	W (g)	Removal (%)	Q (mg/g)
1	0.2000	98.6	3.944
2	0.1900	94.1	3.863
3	0.1800	92.8	3.712
4	0.1700	91.2	3.648
5	0.1600	90.5	3.620

Note: Sorbent in a 20 mg L^{-1} As(V) solutions at pH 7.5 with the ratio of solid to solution at 5 g L^{-1}.

In order to show the reusability of the AAPTS/SiO_2 sorbent, adsorption–desorption cycle was repeated five times using the same sorbent. The results showed that the AAPTS/SiO_2 sorbent could be used repeatedly without losing their adsorption capacities significantly (Table 5). Adsorption capacity of AAPTS/SiO_2 sorbent decreased about 10% after five repeated adsorption–desorption cycle.

3.4. Application

The effects of H_2O_2 concentration on the removal rates of arsenic and the contents of As(V) and As(III) were investigated by treating ammoniacal etching waste liquor with H_2O_2 solutions of different

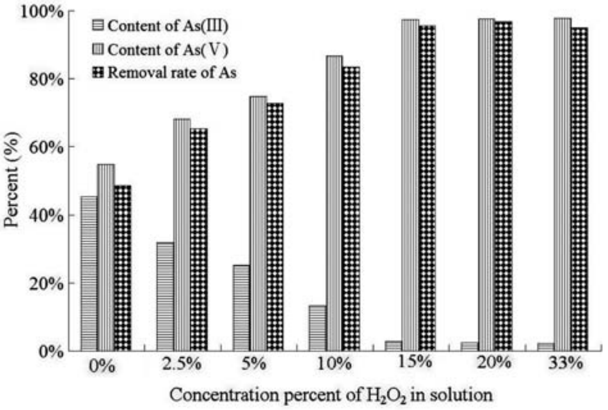

Fig. 7. Effect of H_2O_2 usage on the removal rates of arsenic by AAPTS/SiO_2 from etching waste liquor: Concentration percents range of H_2O_2 in the solution = 2.5–33 (wt.%); volume of etching waste liquor = 20 mL, reaction time = 30 min, pH = 7.5, dosage = 5 g L^{-1}, temperature = 25℃.

concentrations. Fig. 7 shows the H_2O_2 concentration dependence of the removal rates of arsenic and the contents of As(V) and As(III) in ammoniacal etching waste liquor. As seen here, the contents of As(V) ions increased with H_2O_2 contents in the range from 0% to 15% and then the contents of As(V) ions reached a plateau, while the contents of As(III) ions decreased with H_2O_2 contents in range the from 0% to 15% and kept constant after 15%. Results indicated that the solution containing more than 15% H_2O_2 could oxidize effectively As(III) to As(V). There were two reasons for the high dose of H_2O_2. One was the lower oxidation ability of H_2O_2 in the alkaline solution; another was due to the ammoniacal etching waste liquor containing large amounts of ammonia which consumes part of H_2O_2. After the oxidation treatment, the removal rates of arsenic were increased to a different extent in the range of H_2O_2 from 2.5% to 15% and then an equilibrium value was reached in the solution containing more than 15% H_2O_2. The removal rates of arsenic from the ammoniacal etching waste liquor reached 95.4% using the treatment of H_2O_2, while the removal rate of arsenic without H_2O_2 was only 48.5%. It was because the As(V) was adsorbed by AAPTS/SiO_2 sorbent, whereas the As (III) remained in the solution. The concentration of total As was reduced by the treatment of AAPTS/SiO_2 sorbent from 86.5 to 3.8 mg L^{-1} in ammoniacal etching waste liquor. The results indicated that AAPTS/SiO_2 sorbent could remove effectively As from ammoniacal etching waste liquor which was treated by H_2O_2 and effectively controlled the arsenic contents of ammoniacal etching waste liquor. The ammoniacal etching waste liquor treated with AAPTS/SiO_2 sorbent can be used for the preparation of feed-grade tribasic copper chloride feed additive with low levels of arsenic compared with the standard value of tribasic copper chloride feed additive [29].

4. Conclusions

The prepared AAPTS/SiO_2 sorbent exhibits good characteristics, such as good stability, fast adsorption kinetics, high adsorption capacity, and suiting to the removal of arsenic from ammoniacal etching waste liquor. The AAPTS/SiO_2 sorbent can be used in the treatment process of ammoniacal etching waste liquor. The purified ammoniacal etching waste liquor can be used for the production of feed-grade tribasic copper chloride additive.

Supplementary material

The supplementary material for this paper is available online at http://dx.doi.10.1080/19443994.2012.708535.

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