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Cationic surfactant adsorption on silica gel and its application for wastewater treatment

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ABSTRACT

The adsorption of cetyltrimethylammonium bromide (CTAB), a well known cationic surfactant on silica gel and its application for organic bearing wastewater treatment was studied in detail. The study was conducted for both CTAB-spiked distilled water and real wastewater. The studies on adsorbent dose variation and removal kinetics were conducted to find the optimum dose and equilibrium contact time for CTAB removal. Interestingly, the adsorption capacity was found to be very high for real wastewater and the reaction occurred very rapidly compared to that of CTAB-spiked distilled water samples. The kinetic study revealed that the reaction followed the pseudo-second order reaction kinetics model. The isotherm followed four region isotherm models. The effects of various parameters such as pH, presence of electrolytes and operating conditions on the adsorption process were studied. High adsorption capacity was observed in presence of electrolytes and in alkaline condition. Kinetic study determined the rate limiting to be chemisorption. Regeneration of silica gel after its complete exhaustion was efficiently done using hydrochloric acid (18%). After the surfactant removal, the surfactant modified silica gel (SMSG) was efficiently used for the removal of dyes and herbicide from water environment through the process called adsolubilization. Therefore, this would be a simple and efficient process for treatment of organic bearing wastewater especially textile wastewater.

Keywords: Adsorption; Cationic surfactant; CTAB; Silica gel; Herbicide; Dye; Surfactant modified silica gel; Adsolubilization

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1. Introduction

Cationic surfactants (CS) have large applications in various fields like fabric softening, textile industry, road construction, disinfectants, biocides, emulsifiers, wetting agents, processing additives, mining, hair conditioning and cosmetics etc. [1,2]. Such widespread use of CS leads to its massive discharge into the environment causing environmental concern. To protect public health, elimination of CS from wastewater has thus become very important. The reduction of these contaminants has received considerable attention during last few decades [3, 4]. Common technologies that reduce the CS from water environment include ozonation or advanced oxidation process [5], adsorption [4,6–12] and biological processes [13–15].

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Removal by ozonation was found to be expensive and difficult for field application. As most of the cationic surfactants are biocidal, biological process would not be effective in high concentrations (>20 mg/l) [6]. Hence, adsorption appears to be the most effective process that can be easily applied in the filed. Among the various adsorbents, the uses of natural clay minerals like zeolite, bentonite, sepiolite etc. [4,6,8] have drawn much interest since these are abundant and also cheap commodities. However, industrial application requires answers to some basic questions—ability of regeneration and ease of application in the field [9]. Aerosil (a high purity non porous silica gel) was used for adsorption of cationic surfactant from water environment [10,12]. However, in these studies the works were limited to describe the physicochemical behavior of the adsorption process. Further, the exhausted ionic surfactant coated metal oxide could be reused for removal of various organic and inorganic pollutants from water environment through the newly developed technology called adsolubilization [16–21]. Hence, the present research aims to examine the potential of silica gel (porous) for being used as an adsorbent for the removal of CS from water environment, and further use of exhausted silica gel for removing other organic pollutants through adsolubilization. In the present study, cetyltrimethylammonium bromide (CTAB) was used as a representative of quaternary ammonium based cationic surfactants, since many researchers have considered the same [2,6,8,12]. The broad objectives of the study are (i) to find out the optimum adsorbent dose and equilibrium time for different initial concentrations of CTAB, (ii) to develop the adsorption isotherm, (iii) to investigate the effects of different interfering substances and operating conditions, (iv) to see the effectiveness of silica gel for treatment of CTAB-bearing real wastewater, (v) regeneration of adsorbent and its reuse for CTAB removal, and (vi) further use of the surfactant modified silica gel (SMSG) for dye and herbicide removal. In this study, methyl orange (MO) and methylene blue (MB) as representatives of organic anionic and cationic dyes respectively and 2,4-dichlorophenoxyaceticacid (2,4-D) as representatives of herbicides were considered.

2. Materials and methods

2.1. Reagents

Orange II (Hi-Media, India), cetyltrimethylammonium bromide (Hi-Media, India), 2,4-dichlorophenoxyaceticacid (2,4-D) (Merck, Germany), methylene blue (MB), methyl orange (MO) and chloroform (Merck, India) were used as received. All other chemicals used in this study were of high purity and used without further purification. All the chemicals were of Analytical Reagent Grade.

2.2. Adsorbent

Silica gel was supplied by Merck, India and used without further grinding and sieving. The granulation of silica gel was 60–120 mesh (Indian Standard) and the corresponding particle size range was 0.125 to 0.250 mm. The zero point charge of silica gel has been reported to be 2 [22].

2.3. Instrumentation

A high precision electrical balance (CP 225D, Sartorious GMBH) was used for weighing. Digital pH meter (PB-11, Sartorious GMBH) was used for pH measurements and a spectrophotometer (UV-1800, Rayligh, Beiging) was used for absorbance measurement.

2.4. Analytical method

Spectrophotometric method was used for the determination of CTAB in the concentration range 0–12 mg/l [23]. Orange II (0.4×10^{-3} M) chemically known as p-(β-naptholazo) benzene sulfonic acid as ion pairing agent with CTAB and chloroform as an extraction solvent were used. The relation between absorbance and concentration at 485 nm wavelength has been determined as *Absorbance = 0.0399 × Concentration (mg/l) + 0.0377* ($R^2 = 0.9965$).

MO and MB were measured in the concentration range of 0–12 mg/l by spectrophotometric method at a wavelength of 470 nm and 663 nm respectively. The relation between absorbance and concentration was found as *Absorbance = 0.071 × Concentration (mg/l) + 0.0428* ($R^2 = 0.9999$) for MO and *Absorbance = 0.1539 × Concentration (mg/l) + 0.0785* ($R^2 = 0.9971$) for MB.

Similarly, 2,4-D was quantified by spectrophotometer method in the concentration range of 0–35 mg/l [24]. The relation between absorbance and concentration was found as *Absorbance = 0.0396 × Concentration (mg/l) + 0.0377* at 230 nm wavelength ($R^2 = 0.9995$) and *Absorbance = 0.0091 × Concentration (mg/l) + 0.0255* at 283 nm wave length ($R^2 = 0.9995$). It was observed that the values from above two equations are almost same and average of the two values was taken.

2.5. Experimental studies

The batch experiments on the removal of CTAB were carried out at a temperature of 30 ± 2 °C with CTAB-spiked distilled water samples prepared in laboratory as well as with real wastewater collected from a large scale textile industry situated at Hooghly, India. The industrial wastewater contained 65 mg/l of CS in terms of CTAB. The samples were shaken in a mechanical shaker at a shaking speed of 140 rpm. A sample volume of 100 ml was taken for all the experiments. Effects of adsorbent dose and contact time for CTAB-spiked distilled water samples (having initial concentration of 50, 500, 1000 and 2000 mg/l) and real wastewater were studied. Experiments on such high concentration range have been carried out by different researchers [6,8–9,11,13–14]. The adsorbent dose and contact time was varied from 0–50 g/l and 0–45 mins. respectively.

Surfactant bearing real wastewater generally contains various electrolytes which may interfere with the performance of adsorbent. Therefore, it is required to investigate the effect of various interfering substances on removal process. The effects of different interfering substances like pH (in the range of 3–11), sodium chloride (0–11.2 mM or 655 mg/l), magnesium sulfate (0–10.4 mM or 1250 mg/l), sodium sulfate (0–0.42 mM or 60 mg/l), ferric sulfate (0–0.34 mM or 138 mg/l), temperature (15–35 °C) and shaking speed (90–210 rpm) were studied for CTAB-spiked distilled water samples having initial CTAB concentration of 2000 mg/l with silica gel dose of 30 g/l. The range of added electrolytes was selected on the basis they are normally present in water or wastewater. Generally the wastewater contains iron in very low concentrations and hence the concentration of ferric sulfate was kept in lower range compared to sodium chloride and magnesium sulfate. As the effect of ferric sulfate was compared to that of sodium sulfate, the concentration of sodium sulfate was also taken in lower range. The contact time in each case was 30 mins. The pH of synthetic samples was at 6.9 ± 0.1, except for the experiments to see the effect of pH. The adsorption isotherm wa s drawn to understand the nature of the equilibrium distribution of CTAB on the surface of silica gel. In this study, the initial CTAB concentration was varied from 0 to 20000 mg/l and the adsorbent dose was kept fixed at 30 g/l.

After removal of the CTAB, the exhausted silica gel was regenerated using dilute hydrochloric acid and was reused for the same purpose. Furthermore, the surfactant modified silica gel after CTAB adsorption was used for the removal of MO, MB and 2,4-D at different surfactant surface coverage from water environment. The different surfactant surface coverage on silica gel was obtained using varying concentration of CTAB bearing distilled water which was adsorbed on fixed dose of silica gel (30 g/l).

In all the above cases, after shaking the sample, it was allowed to settle for 5 min and then filtered through ordinary filter paper and used for analysis.

In all the above cases, except for calibration curves the experiments were conducted for atleast three times and the mean values were taken for plotting the curves. The calibration curves were plotted taking the mean value of six determinations. The maximum standard deviation (SD) was reported in respective figures.

2.6. Analysis of reaction kinetics data

In order to investigate the mechanism of solute adsorption onto the adsorbent, four kinetic models viz., first order reaction model [25] based on the solution concentration, pseudo-first order equation of Lagergren [26] based on the solid capacity, second order reaction model based on the solution concentration [25] and pseudo-second order reaction model based on the solid phase sorption [27] were analyzed and a comparison of the best fit sorption mechanism was made.

The linearized forms of different reaction models are shown below.

First order: $\ln C_t = \ln C_o - K_1 t$

Pseudo first order: $\dfrac{dq_t}{dt} = K_{S1}\left(q_e - q_t\right)$

Second order: $\dfrac{1}{C_t} - \dfrac{1}{C_o} = K_2 t$

Pseudo second order: $\dfrac{t}{q_t} = \dfrac{1}{K_{S2}q_e^2} + \dfrac{1}{q_e}t$

The experimental reaction kinetics data were analysed using the above four kinetic models.

3. Results and discussion

3.1. Effect of adsorbent dose on CTAB uptake by silica gel

Since the adsorbent dose has significant effect on the removal of CTAB, the effect of this parameter was studied. The effect of dose for different initial concentrations are shown in Fig. 1. The optimum adsorbent doses were found to be 7.5, 15, 20 and 30 g/l for initial CTAB concentration of 50, 500, 1000 and 2000 mg/l respectively. At this stage, the removal of CTAB was found to be 95, 90, 80 and 59% respectively. The increase in the removal efficiency with the increased adsorbent dose could be attributed to the increased area of sites available for adsorption. The contact time for each case was 30 min.

Experiments were carried out to find the effectiveness of silica gel for removing CS from real industrial wastewater. The water quality parameters for the sample water were found out. The CS concentration, pH, total dissolved solids, turbidity and COD were 65 mg/l (in terms of CTAB), 9.2, 700 mg/l, 400 NTU and 1040 mg/l respectively. The effect of adsorbent dose was studied in the range of 0–5 g/l and the contact time and shaking speed were 30 mins. and 140 rpm respectively. The optimum adsorbent dose was observed to be very low (0.75 g/l). The removal efficiency was 97% (Fig. 1). The effluent quality also improved. The effluent pH, TDS, turbidity and COD were found to be 8.1, 576 mg/l, 100 NTU and 250 mg/l respectively. It was very interesting to observe that the removal of CS was more in real wastewater compared to that for CS-spiked distilled water. The reason behind this is that the large quantity of dissolved solids and the high pH of the wastewater increase the adsorption capacity. This is also evidenced from the fact that in case of CS-spiked distilled water the removal efficiency increased as the pH and the concentration of the different electrolytes are increased (as discussed in section 3.4 and 3.5).

3.2. Kinetic studies on CTAB uptake by silica gel

In order to find out the equilibrium contact time for CTAB uptake by silica gel kinetics study was carried out taking the respective optimum doses for various initial concentrations. The shaking time varied from 0 to 45 mins. It was found that the rate of adsorption was very rapid initially (Fig. 2) and found to be steady after 10 min for 50 mg/l, 20 min for 500 mg/l and 30 min for 1000 and 2000 mg/l. For real wastewater the value was found to be slightly less than 10 min. Thus, a reaction time of 30 min could be sufficient for all practical purposes in the above mentioned concentration range.

Table 1
Equations and R^2 values of the linear fit lines of pseudo-second order reaction models for the removal of CTAB spiked in distilled water and from real wastewater by silica gel

Initial Concentration	Equation	R^2
50 mg/l	$t/q_t = 0.165\,t + 0.1567$	0.9998
500 mg/l	$t/q_t = 0.033\,t + 0.0845$	0.9993
1000 mg/l	$t/q_t = 0.216\,t + 0.1042$	0.9972
2000 mg/l	$t/q_t = 0.0197\,t + 0\,.1201$	0.9996
65 mg/l (real wastewater)	$t/q_t = 0.0115\,t + 0.0075$	0.9999

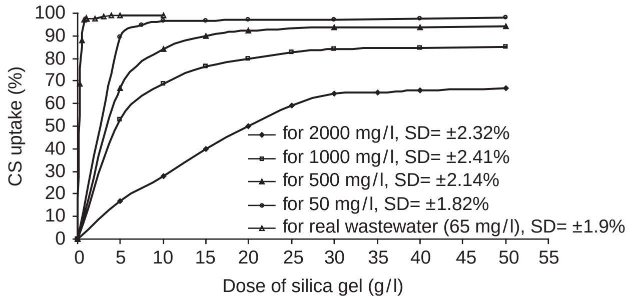

Fig. 1. Effect of adsorbent dose on CTAB uptake by silica gel.

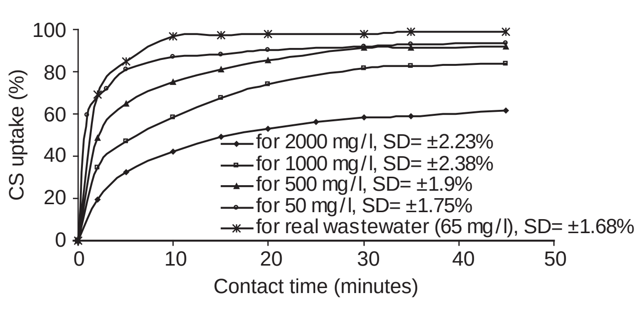

Fig. 2. CTAB uptake by silica gel with respect to contact time.

The rate of sorption was determined by testing the four reaction kinetics models as described in section 2.6. After analyzing the four models, it was found that the pseudo-second order fitted best among the other models which indicated that the rate-limiting step for the CTAB removal by silica gel was chemical adsorption or chemisorption [27]. The equations of the pseudo-second order model and the determining coefficients (R^2) are shown in Table 1. The value of reaction constant was found to be 0.0176 g/mg-min for real wastewater. The reaction constant, so found, could be used for the design of different types of batch reactors generally used in the field. The pseudo-second order kinetic model could be used for the rough estimation of the adsorption capacity of CTAB uptake by silica gel. The adsorption capacity was found to be 86.95 mg/g for real wastewater.

3.3. Adsorption isotherm and mechanism

The adsorption isotherm of CTAB on silica gel surface at neutral pH is shown in Fig. 3. Generally the isotherms, plotted in log-log scale, for ionic surfactant adsorption on oppositely charged surfaces are divided into four regions [28]. The present adsorption isotherm also showed the four distinct regions. The region I occurred at a very low equilibrium concentration (below 0.38 mg/l or 1.04×10^{-6} M of CTAB). The CTAB molecules are adsorbed as monomers in this zone I and the adsorption is due to electrostatic forces between positively charged CTAB ions and the negatively charged silica gel surface. In addition to electrostatic force, the CTAB molecules are adsorbed due to interaction between them in zone II. Thus monolayer, partial bilayer or bilayer structures of surfactant were formed on silica surface. The transition from region II to III occurred at an equilibrium concentration of 4.29 mg/l (1.17×10^{-5} M) of CTAB. The adsorption in the zone III is due to the association between the hydrocarbon chains and this region occurs at a concentration near CMC of the surfactant.

The critical micelle concentration of CTAB is 1×10^{-3} to 1.3×10^{-3} M. The transition from zone III to IV occurred at an equilibrium concentration of 5359.3 mg/l (1.47×10^{-2} M) which is well above critical micelle concentration of CTAB. In this zone the CTAB molecules formed completely bilayer structure on the silica surface and the surface charge was completely reversed that showed strong affinity towards anions [17]. From this isotherm study the maximum adsorption capacity was found to be 71.35 mg/g (195.77 mmol/kg) and it occurred when initial concentration of CTAB was 7500 mg/l (2.06×10^{-2} M). The capacity so obtained, was comparable with the CTAB sorption capacity of kaolinite (60 mmol/kg) and zeolite (200 mmol/kg) and that were obtained at 200% cation exchange capacity and external cation exchange capacity of kaolinite and zeolite respectively [17,29].

The plot in Fig. 3 also shows that the adsorption of CTAB on silica gel followed the Freundlich isotherm model which indicated that the surface of the silica gel was heterogeneous. This was due to the different types of silanol groups present on the silica surface. It is important to mention here that in the present case the adsorption of CTAB on silica gel did not follow Langmuir isotherm model well. The adsorption capacity constant and affinity constants varied from region to region. The values of the isotherm equation, constants and determining coefficients (R^2) for linear fit line are given in the Table 2. The affinity constant was found to be maximum for region II indicating sharp increase in adsorption capacity.

3.4. Effect of pH on CTAB uptake by silica gel

The pH of an aqueous medium plays an important role that influences the uptake of the adsorbate. Fig. 4 shows the plot of CTAB uptake by silica gel at different pH. Higher pH was favorable for CTAB adsorption and as the pH increased the adsorption capacity gradually increased. Adak et al. [19] and Somasundaran et al. [28] showed that adsorption of sodium dodecyl sulfonate, an anionic surfactant on positively charged alumina was strongly pH dependent. The adsorption capacity of sodium dodecyl sulfonate on alumina decreased with the increase in pH. In the present case, the opposite behavior of the above case was expected since the surfactant was cationic and silica surface was negatively charged. At high pH, the silica particles (having low zero point charge, $pH_{pzc} = 2$) became more negative and thus there was a significant enhancement in adsorption.

3.5. Effects of electrolytes on CTAB uptake by silica gel

Since the real wastewater generally contains different salts which may interfere uptake of adsorbate, the experiments were carried out to see the effects of

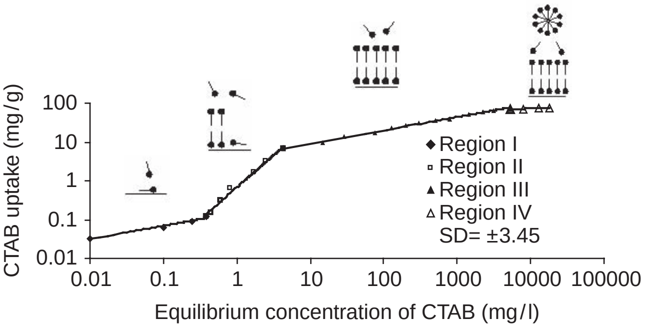

Fig. 3. Adsorption isotherm of CTAB uptake by silica gel.

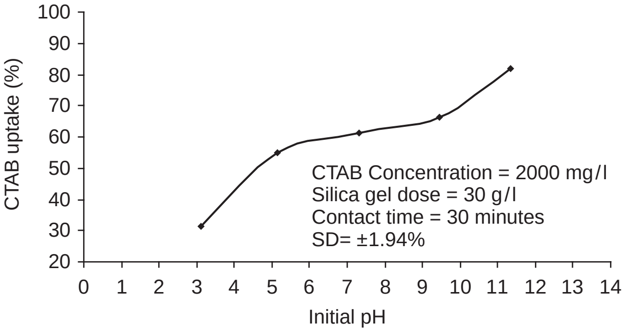

Fig. 4. Effect of pH on CTAB uptake by silica gel.

Table 2
Constants of Freundlich isotherm model for CTAB uptake by silica gel

Region	Equation	R^2	Adsorption capacity constant, K_f [(mg/g)(l/mg)$^{1/n}$]	Affinity constant, *1/n*
I	$\ln q_e = 0.3414 \ln C_e - 1.8782$	0.978	0.1528	0.3414
II	$\ln q_e = 1.6533 \ln C_e - 0.3891$	0.9877	0.6776	1.6533
III	$\ln q_e = 0.3432 \ln C_e + 1.4116$	0.9947	4.1025	0.3432
IV	$\ln q_e = 0.02332 \ln C_e + 4.0662$	0.9258	58.3348	0.02332

different electrolytes like sodium chloride, sodium sulfate, ferric sulfate, and magnesium sulfate (spiked in distilled water) on adsorption process. It was observed that in presence of each electrolyte the uptake of CTAB increased (Figs. 5 and 6). The increase in adsorption of ionic surfactant on oppositely charged surface in presence of electrolytes has been reported by different researchers [19, 30–33]. The presence of different electrolytes increased the ionic strength of the solution which in turn, decreased the CMC [31]. It was found from the isotherm study that at a concentration near CMC of the surfactant molecules were adsorbed to form bilayer structure having better adsorption capacity. Thus, the presence of electrolytes resulted in more CTAB adsorption.

Again, with the increase of electrolyte concentration, the electrical double layer on the surface of the adsorbent is compressed and the electrostatic repulsion between adsorbed surfactant species decreased, which resulted in the increase of adsorption capacity [30,32]. It was observed from the Figs. 5 and 6 that the adsorption capacity increased in the order of ionic strength of electrolytes present in the solution. The greater capacity obtained in presence of $MgSO_4$ than NaCl (Fig. 5). Fig. 6 suggested that presence of $Fe_2(SO_4)_3$ would enhance the adsoprtion than Na_2SO_4. The effect of Na_2SO_4 in the lower concentration range (0–0.42 mM) was not significant.

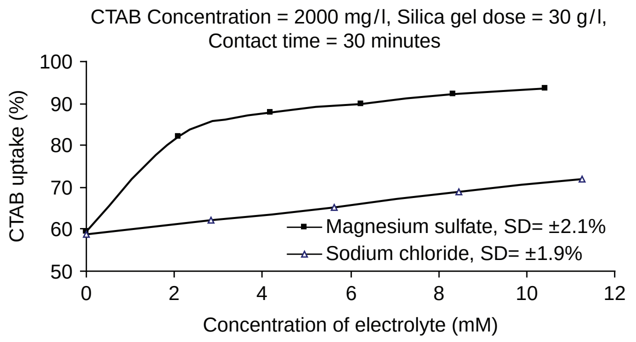

Fig. 5. Effect of sodium chloride and magnesium sulfate on CTAB uptake by silica gel.

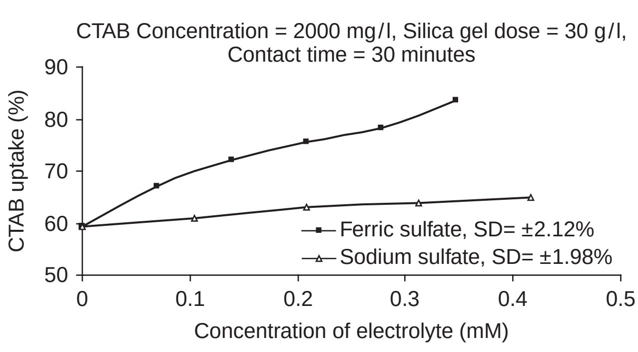

Fig. 6. Effect of sodium sulfate and ferric sulfate on CTAB uptake by silica gel.

3.6. *Effect of operating conditions on CTAB uptake by silica gel*

Temperature and shaking speed are the two operating conditions which may influence the adsorption capacity. Adsorption of CTAB on silica gel was studied at different temperature in the range of 15–35 °C. It was found that the temperature had no significant effect on the CTAB uptake by silica gel.

The rate of shaking in batch study may have influence on the adsorption process. If the process is limited by film diffusion, then the increase/decrease in the shaking speed will increase/decrease the adsorption capacity. So effect of shaking speed was studied in the range of 90–210 rpm. No significant effect of shaking speed was observed which indicated that the film diffusion was not the rate limiting.

3.7. *Regeneration of exhausted silica gel*

The regeneration of the exhausted silica gel was done efficiently by 18% hydrochloric acid with a dose of 500 g/l (pH less than 1). Regenerated silica gel was again used for further uptake of CTAB. The efficiency of regenerated silica gel was found to be slightly less (~3–4%) than the fresh material.

3.8. *Reuse of surfactant modified silica gel for removal of MO, MB and 2,4-D*

As discussed in section 3.3, adsorption of CTAB on negatively charged silica gel surface occurred due to electrical attraction between negatively charged surface and cationic head groups of CTAB and also due to the interaction between the long hydrocarbon chains of surfactant molecules to form monolayer, partial bilayer or bilayer structure depending on surfactant concentration [29]. The silica gel having such surfactant coated structure on its surface; called surfactant modified silica gel (SMSG), could effectively be used for solubilization of various organic pollutants (e.g. dye, herbicide etc.) from water environment. This process is called adsolubilization

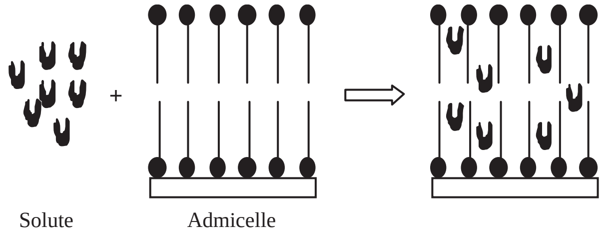

Fig. 7. Schematic representation of Adsolubilization process.

(Fig. 7). Thus the surfactant coated silica gel could be reused for treatment of organic bearing wastewater.

Therefore, the exhausted silica gel was used for the removal MO (an anionic dye), MB (a cationic dye) and 2,4-D. This study was carried out to see the removal efficiencies in varying doses of silica gel with bilayer surfactant coverage (71.35 mg/g) as obtained in the isotherm study at the initial CTAB concentration of 7500 mg/l. In this study, the pH of the solutions was 8 ± 0.1 for MO, 7 ± 0.1 for MB and 4.0 ± 0.1 for 2,4-D. The study determined the optimum SMSG dose to be 3.5, 8 and 12 g/l and the corresponding removal efficiency was found to be 97%, 92% and 94% for MO, MB and 2,4-D respectively (Fig. 8). It was observed that in case of MO removal (anionic dye) the efficacy of SMSG was much higher than that of MB. It was interesting to see that the removal of MB was also good though it was cationic in nature that would have been repulsed by cationic surfactants of SMSG. There are such examples like aniline and MB (cationic species) adsolubilization on cationic surfactant modified zeolite and montmorillonite respectively [21,34]. The removal of those compounds was due to loosely packed bilayer cationic surfactant, incomplete dissociation of the compounds and ion exchange onto the bare surface of the silica gel.

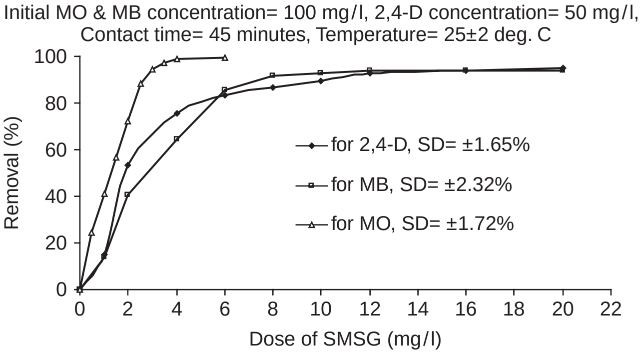

Fig. 8. Performance of SMSG for removal of dye and herbicide.

Since the surfactant molecules formed monolayer, partial bilayer or bilayer structure on silica gel surface depending on surfactant concentration, there should be an effect of surfactant surface coverage on uptake of ionic species from water environment. To see this effect, the experiment was conducted for removal of MO, MB and 2,4-D at different surface coverage taking the SMSG dose as 4g/l and the result is shown in Fig. 9. It was observed that for anionic species like MO and 2,4-D, the removal was increased with increase of surfactant surface coverage. This was due to solublization of organics within the surfactant layer and also due to the affinity of anions towards the positive charge of the CTAB bilayer. Similar trend was observed in case of arsenite and arsenate removal by surfactant coated zeolite and kaolinite [17]. It was interesting to observe that the sorption of 2,4-D at zero surfactant surface coverage (i.e. by fresh silica gel) was nil. But in case of MB, the higher removal was obtained at lower CTAB coverage on silica gel (16 mg/g) than others, which suggested that complete bilayer was not formed at this stage and thereby full conversion of surface charge of silica gel from negative to positive (by CTAB bilayer) was not achieved and hence, it showed better affinity towards cationic species. The MB removal was gradually decreased at the surface coverage of 42 and 71.35 mg/g. At higher CTAB coverage, the positive charge of bilayer structure repulsed the cationic MB species. Similar decreasing trend was found in sorption of aniline at pH 3.6 (where positively charged anilinium were present more than 90% of the aniline in solution) by CTAB modified zeolite at higher surfactant coverage [21].

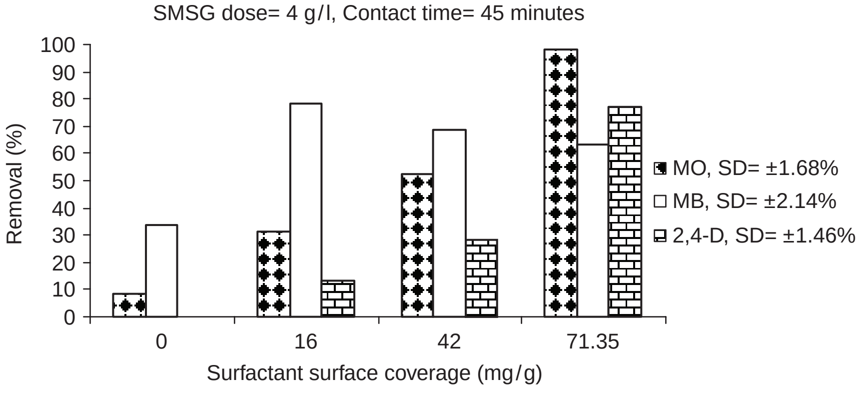

Fig. 9. Effect of surfactant surface coverage on uptake of MO, MB and 2,4-D.

4. Conclusion

Silica gel could effectively be used for the adsorption of CS from both CS-spiked distilled water and industrial wastewater. The adsorption capacity of silica gel increased dramatically in presence of various salts and at higher pH. The adsorption followed a four-region isotherm model. There was no significant effect of operating condition on the adsorption process. Kinetics study showed that the rate limiting step was the chemisorption. The removal efficiency and adsorption capacity was found to be much higher for real industrial wastewater compared to those for distilled water spiked samples. After the removal of CTAB, the exhausted silica gel was regenerated by dilute HCl. The exhausted silica gel, so called SMSG, was also efficiently used for the removal of herbicide and dyes from aquatic environment through the recently developed separation technology called "Adsolubilization". The adsolubilization of organic pollutants was strongly dependent on the surfactant coverage on silica gel surface. Thus, the silica gel could be successfully used for the treatment of organic wastewater especially textile wastewater which contains both cationic surfactant and dyes.

Symbols

C_t — solute concentration at any time t
C_o — solute concentration at time $t = 0$
C_e — equilibrium solute concentration
q_t — amount of solute adsorbed per unit weight of adsorbent at any time t
q_e — amount of solute adsorbed per unit weight of adsorbent at equilibrium
K_{S1} — pseudo-first order reaction rate constant
K_2 — second order reaction rate constant
K_{S2} — pseudo-second order reaction rate constant
K_f — Adsorption capacity constant
$1/n$ — Affinity constant

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