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## Sorption and transport studies of cetyl trimethylammonium bromide (CTAB) and Triton X-100 in clayey soil

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### Abstract

Surfactants are soil washing agents and facilitators for subsurface remediation of hydrocarbon spills. It is important to understand the sorption and transport behavior of surfactants for enhanced soil remediation. The adsorption and desorption isotherms of cetyl trimethylammonium bromide (CTAB) and Triton X-100 with sand and kaolinite have been quantified. Kaolinite clay had the highest sorption capacity compared to blasting sand. Transport parameters such as diffusion coefficient ( $D$ ) and retardation factor ( $R$ ) of the above mentioned surfactant solutions were determined in clayey soils (82.5% sand and 17.5% kaolinite mixture) with near zero and 0.1 g/L ionic strength. NaCl was used as the electrolyte solution. Convection-Diffusion equation was used to model the breakthrough curves of the surfactants. Bromide ion was chosen as the tracer material in order to characterize the column. CTAB and Triton X-100 were used to flush the perchloroethylene (PCE) contaminated soil. The effectiveness of CTAB and Triton X-100 in flushing the PCE from the contaminated soil was quantified.

**Key words:** surfactant; sorption; transport; clayey soil

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### Introduction

Surfactants have been studied and evaluated for many years primarily for their application in cosmetics, drug delivery and enhanced oil recovery from oil reservoirs. Recently, surfactant enhanced remediation of dense non aqueous phase liquids (DNAPL) contaminated aquifer has been tested in field scale experiments (Deepak and Kishore, 2001). The relatively slow dissolution of non-aqueous phase liquid (NAPL) contaminants into groundwater has prompted investigation of nonionic and other surfactants as potential solubilizing agents for enhanced dissolution and removal of NAPL from the subsurface. A major concern in the choice of a solubilizing agent, in addition to its solubilizing capacity for the contaminant is its tendency to sorb to aquifer sediment (Chu, 2003; Lee et al., 2004; John et al., 2000).

The understanding of surfactant adsorption is importance for the application of surfactants for enhanced oil recovery and for surfactant enhanced soil remediation. Adsorption of surfactants is detrimental for these applications as it results in surfactant loss and reduced surfactant mobil-

ity. Furthermore, adsorption of surfactants may create new adsorption sites for hydrophobic compounds (Grolimind et al., 1998; Litton and Olson, 1994; Jawitz et al., 1998). Many commercially available surfactants such as linear alkylbenzenesulfonates and alcohol ethoxylates consist of multiple components. Natural surfactants also often are mixtures. Multicomponent surfactants may change in composition during adsorption and transport, which can result altered surface properties. Insight into the adsorption behaviour of multicomponent surfactants thus is needed for understanding surfactant transport and for optimal design of surfactant mixtures (Shukla et al., 2002; Noordman et al., 2000).

It has also been recently shown that surfactant sorption to sediment not only decreases the aqueous surfactant concentration, thereby reducing surfactant solubilizing capacity, but also increases the proportion of contaminant (e.g., dissolved NAPL) that is bound to the stationary phase. As a result the equilibrium constant for distribution of contaminant between mobile (dissolved and micellar) and stationary (sediment and sediment sorbed surfactant) phases,  $K_d$  may actually change in the presence of surfactant (Kallay et al., 1983; Zhou and Selim, 2001; Torrens et

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al., 1998).

The presence of widely different surfactant components in the surfactant mixture may greatly influence its behavior in the subsurface, potentially producing different transport behaviors for different surfactant mixtures with the same bulk properties. An understanding of the sorption and transport of mixed surfactants may be important for optimization of surfactant-based aquifer remediation methods for specific sites and contaminants in order to minimize surfactant sorption losses and to prevent unwanted mobilization of nonaqueous organic contaminants. If selective sorption of surfactant components occurs, it is important to ensure that the composition of the surfactant remaining in solution is appropriate for solubilization of the contaminants of interest and the sorbed surfactant does not have great affinity for the contaminants of interest, potentially slowing the remediation process. The mixed sorption behavior of polydisperse surfactants may also have important implications for their bioavailability after the remediation operation has concluded (Kibbey and Hayes, 1997).

Characterization of the sorption behaviour of non ionic surfactants is complicated by the fact that non ionic surfactants are Poisson-distributed mixtures of oligomers of varying chain lengths, such that certain oligomers may undergo stronger sorption to aquifer materials, and these oligomers may or may not be important in solubilization (John et al., 2000). In this study, Triton X-100 was chosen to represent non ionic surfactant which is mainly used in field studies. Cationic surfactants have strong adsorption on colloid surfaces, and changes colloid surfaces properties. CTAB is again widely used cationic surfactant in field studies. The amount of clay present in soil varies the transport and sorption parameters of surfactants. Our experiments were carried out around  $10^{-4}$  cm/sec permeability. The main objective of this article is to investigate CTAB and Triton X-100 transport and sorption parameters mainly in clayey soil. The overall objective of this study is to determine the transport and sorption properties of CTAB and Triton X-100 in clayey soil and to find out the efficiency of these surfactants to remove PCE from contaminated soil.

The specific objectives are as follows: (1) determine the transport parameters of CTAB and Triton X-100 in sandy clayey soil; (2) determine the sorption parameters of CTAB and Triton X-100 in sandy clayey soil; (3) flush the PCE contaminated soil using CTAB and Triton X-100.

## 1 Materials and experiments

### 1.1 Materials

The blasting sand was obtained from TEC minerals of Eagle Lake, TX, USA. Sand particles are made mostly of quartz and feldspar and have a very stable tetrahedral structure. The particle size ranged from 0.07 to 5 mm.

The specific gravity was 2.65. Clays have marked effects on both the physical and chemical properties of the soils because of their comparatively large surface area and permanent negative surface charge. Hydrite-R kaolinite was purchased from D&F Distributing Inc. and its properties are listed in **Table 1** as specified by manufacturer's data sheet. The isomorphous substitution of Al(III) for Si(IV) and Mg(II) substituting for Al(III) gives rise to a net negative charge on its surface. Kaolinite clay is made up of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{H}_2\text{O}$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$  oxides. The specific surface of kaolinite clay is in the range of 5–30  $\text{m}^2/\text{g}$  and their cation exchange capacity is in the range of 15–20 meq/kg. Cetyl trimethyl ammonium bromide (CTAB) and Triton X-100 were purchased from Sigma-Aldrich, St.Louis, Missouri.

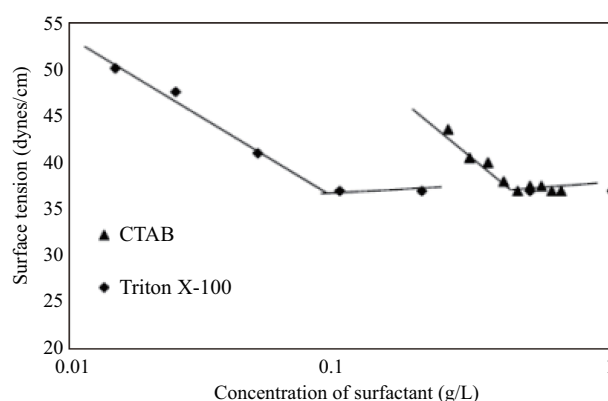
### 1.2 Experimental methods

The cohesive forces between liquid molecules are responsible for the phenomenon known as surface tension at the liquid-air interface. The variation of surface tension for each of the surfactant with the concentration of surfactant is shown in **Fig. 1**. The critical micelle concentration (CMC) for Triton X-100 and CTAB were 0.13 and 0.40 g/L respectively. The surface tension at CMC was 37 dynes/cm (**Fig. 1**).

The gas chromatography (GC) analysis was done using the Shimadzu GC-14A GC with flame ionization detector and a CR501 data processor. The stainless steel column (Alltech) has a 6-ft. length  $\times$  1/8-in. outer diameter  $\times$  0.085-in. inner diameter. The main component of GC

**Table 1** Properties of materials from manufacturer's data sheet and current study

Properties	Sand	Kaolinite
Density ( $\text{g}/\text{cm}^3$ )	2.65	2.58
Natural water content	0.006	0.04
Hydraulic conductivity ( $\text{cm}/\text{sec}$ ) (current study)	0.050028	0.0000012
Porosity (%)	44.4	81.8
Organic carbon (%) (current study)	0.35	1.9



**Fig. 1** Variation of surface tension with surfactant concentration.

included a chemically-inert carrier gas. The carrier gas used is helium. Oven, injection, and detection temperatures were set at 100, 150, and 250°C, respectively. The sample was vaporized and transported through the column by the flow of inert, gaseous mobile phase (air). The column itself contained a liquid stationary phase which was adsorbed onto the surface of an inert solid. The injection volume of sample used for GC analysis was 2 µL. The detection limit for PCE was 1 mg/L. The flow rates of air, hydrogen and helium were 110, 1, and 1 mL/min respectively.

### 1.2.1 Tracer experiments

Tracer breakthrough curves were analyzed to determine Peclet number and column porosity. From the first and second moments of the bromide (Br<sup>-</sup>) breakthrough curve, the average travel time of the tracer and the dispersion coefficient were calculated. Bromide concentrations were measured using electrode. Fitting the convective-dispersive transport equation to the Br<sup>-</sup> breakthrough data using non linear least square procedure gave very similar results. The porosity varied from 0.4 to 0.5.

### 1.2.2 Batch studies

Blasting sand and kaolinite clay was used for adsorption and desorption study of surfactant solutions. Batch sorption experiments were conducted at room temperature. Surfactants of different kinds were prepared in different concentrations. Those solutions were transferred to 40 mL EPA vials with sand. After 21 days of end over end rotation (15 r/min) of tumbler the incubation vials were centrifuged and subsequently the clear supernatant was filtered (0.2 µm) and analyzed for the total aqueous surfactant by gas chromatography using back titration method.

### 1.2.3 Characterization of columns used for transport studies

The experimental setup for the column studies is the column having 5.1 cm diameter and 50 cm long made out of glass which is equipped with air compressor and pressure regulator unit which is used to pump the solutions. Two columns were used for kaolinite clay. In both cases the same type of blasting sand were used (Fig. 2).

### 1.2.4 Surfactant experiments

CTAB and Triton X-100 solutions were prepared in 1 L volumetric flask and were stirred for at least 2 hr for proper mixing before passing through the column. Steady state, unsaturated flow was established in two columns packed with blasting sand and kaolinite. Then the surfactant solutions CTAB and Triton X-100 were pumped through the column and the effluent was collected in tubes with increasing pore volumes.

The surfactant concentrations were measured as follows. The solubility of PCE with the above mentioned surfactants was analyzed using GC. Glass bottles of 200 mL will be filled with surfactants, PCE and water, were sealed with

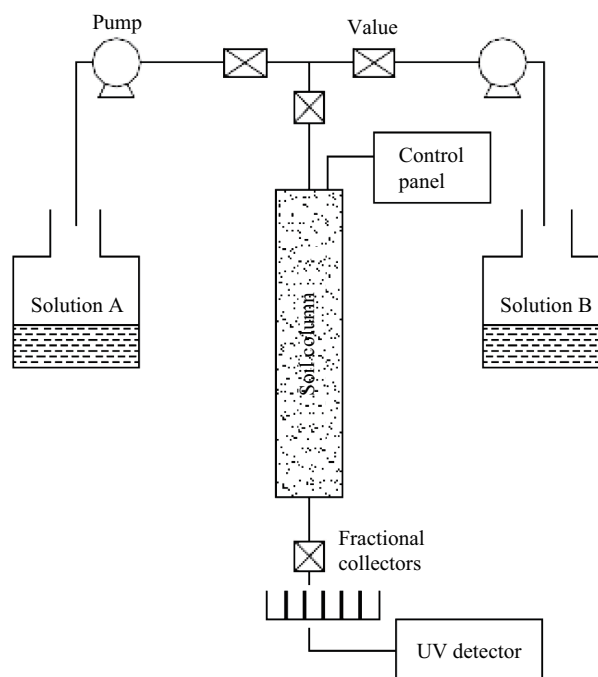


Fig. 2 Schematic drawing of the experimental setup used for breakthrough experiments.

Teflon-lined screw caps. The magnetic stirrer was used for the mixing purposes. The solution was mixed at 750 r/min for 1 hr.

PCE (300 g) contaminated 1200 g sand (82.5%) with kaolinite (17.5%) was sealed thoroughly in order to prevent any losses. After 2 months it was packed with the column. Then water was flushed through the column until there was no measurable PCE found in the effluent. Then 5 g/L CTAB and Triton X-100 solutions were flushed in the column for further PCE removal. The breakthrough curves were plotted.

### 1.2.5 Two-region mobile/immobile model

Consider a laboratory column containing a uniform natural porous medium at saturated flow conditions and constant solution composition. Transport of colloidal particles can be described by accounting for particle advection, hydrodynamic dispersion and deposition (filtration). The concentration of suspended colloidal particles  $c(x, t)$  at a column depth  $x$  and time  $t$  follows the one dimensional advection dispersion equation with a sink term for particle deposition (Van Genuchten and Parker, 1984).

$$\frac{dc}{dt} = D \frac{d^2c}{dx^2} - v \frac{dc}{dx} - kc \quad (1)$$

where,  $v$  is the interstitial velocity of the colloidal particles,  $D$  is the hydrodynamic dispersion coefficient and  $k$  is the particle deposition rate coefficient. The transport equation assumes particle deposition to follow first order kinetics and to be irreversible. Both assumptions are justified at sufficiently low particle concentration and for moderate

to high ionic strengths where particle release is negligible compared to particle deposition. Two site kinetic models developed by Van Genuchten and Parker (1984) was used to determine the transport parameters. Following the notation of Van Genuchten and Parker, Type-1 sites are mobile phase and Type-2 sites are immobile phase.

Consider a soil system composed of a liquid phase involving convective and dispersive transport, and a two region solid phase with decay. In two region model, the sorption rate is thought to be limited by the rate at which solutes are transported by dispersion to the exchange sites. The conceptualization has led to physical nonequilibrium models that partition soil water into mobile (flowing) and stagnant regions. Convective dispersive transport is confined to a mobile liquid region (subscript m) while the presence of solute in an immobile region (subscript im) depends on liquid dispersion from the mobile to the immobile liquid. The solid phase is also partitioned, in this case into a fraction  $f$  that equilibrates instantaneously with the mobile fluid, and another fraction  $(1-f)$  that equilibrates with the immobile liquid. The transport equation for the mobile liquid phase is given by

$$\frac{\partial \theta_m C_m}{\partial t} = \frac{\partial(\theta_m D_m \frac{\partial C_m}{\partial x} - q C_m)}{\partial x} - J_{a1} - J_{a2} - \theta_m \mu_m C_m \quad (2)$$

where,  $C$  is concentration,  $D$  is dispersion coefficient,  $\theta$  is the volumetric water,  $q$  is volumetric water flux,  $\mu$  is a first-order decay coefficient.  $J_{a1}$  is the transfer rate from the liquid to the solid phase of the mobile region, while  $J_{a2}$  is due to dispersion like exchange between mobile and stagnant liquid zones. Mass balance for the mobile sorbed concentration  $S_m$  is

$$f\rho \frac{\partial S_m}{\partial t} = J_{a1} - f\rho \mu_{sm} S_m \quad (3)$$

where,  $\rho$  is the soil bulk density.

A similar mass balance without convective dispersive terms holds for stagnant region as a whole (subscript im)

$$\frac{\partial \theta_{im} C_{im}}{\partial t} + (1-f)\rho \frac{\partial S_{im}}{\partial t} = J_{a2} - \theta_{im} \mu_{im} C_{im} - (1-f)\rho \mu_{sim} S_{im} \quad (4)$$

The above mentioned basic, two region model equations can be applied to different initial and boundary conditions in order to get the different final solutions. This model was verified and used in many past research works (Van Genuchten and Parker, 1984; Simunek et al., 1999). If  $f = 0$ , it will fall into one region model. Two region model have been applied to fit and predict breakthrough curves from column experiments. This model fitted all breakthrough curves satisfactorily, accounting for the skewness of the rising limb as well as for the smooth transition of the declining limb to the tail of the breakthrough curve. The one region model does not follow the curvature of the

breakthrough tail, leading to an overestimation of the immobilization sites. In concise, surfactant transport can be modeled as two region model. The two region model assumes that the liquid phase can be partitioned into mobile (flowing) and immobile (stagnant) regions (Van Genuchten and Parker, 1984; Jiri et al., 1999). Solute exchange between two regions is modeled as a first order process.

$$\left(1 + \frac{\rho_b f k_d}{\theta_m}\right) \frac{\partial C_m}{\partial t} = D_m \frac{\partial^2 C_m}{\partial x^2} - v_m \frac{\partial C_m}{\partial x} - \frac{\alpha}{\theta_m} [C_m - C_{im}] \quad (5)$$

$$\left(1 + \frac{\rho_b (1-f) k_d}{\theta_{im}}\right) \frac{\partial C_{im}}{\partial t} = \alpha [C_m - C_{im}] \quad (6)$$

where, retardation factor,  $R$  is given by  $R = 1 + \frac{\rho_b (1-f) k_d}{\theta}$ ;  $k_d$  is an empirical distribution coefficient,  $\alpha$  is a first-order kinetic rate coefficient.

The migration of surfactants in the subsurface environment is controlled by several transport properties of the soil. The hydraulic conductivity describes the physical movement of the surfactant solution through the soil, while the movement of surfactant solutions is described by the retardation factor.

The following initial and boundary conditions applied for the transport of surfactants in the column:

Initial condition:  $C(x, 0) = C_i$

Boundary conditions:  $C(0, t) = C_0 \quad 0 < t < t_0$

$= 0 \quad t > t_0$

$$\frac{\partial c}{\partial x}(\infty, t) = 0$$

Breakthrough curves were fitted numerically with experimental data. Bromide ion was chosen as a tracer material in order to characterize the column. The retardation factor, dispersion coefficient and seepage velocity were determined by fitting the two region model with experimental data.

## 2 Results and discussion

Triton X-100 followed Langmuir isotherm in adsorption experiments with and without ionic strength (Table 2, Figs. 3a and 4). In desorption experiments it followed linear isotherm (Table 3, Fig. 3b) except with kaolinite it followed Freundlich isotherm. CTAB followed Langmuir isotherm in adsorption experiments (Table 2, Figs. 6a and 7). In desorption experiments, it followed Langmuir isotherm except with kaolinite, it followed Freundlich isotherm (Table 3, Fig. 6b).

Ionic strength of solution may impact in sorption kinetics (Derjaguin and Landau, 1941). In natural sediments, repulsive double-layer interactions resulting from the negative surface charges of the colloidal particles and

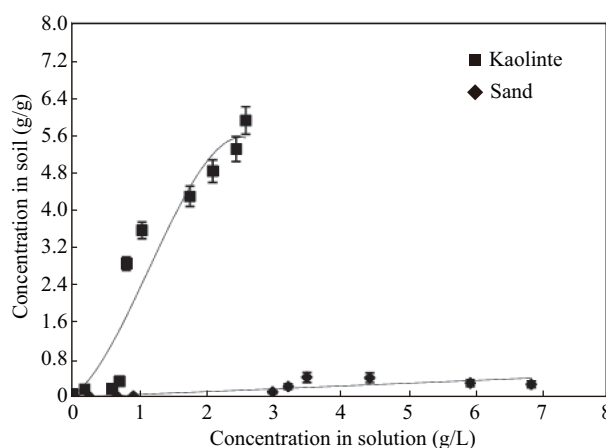
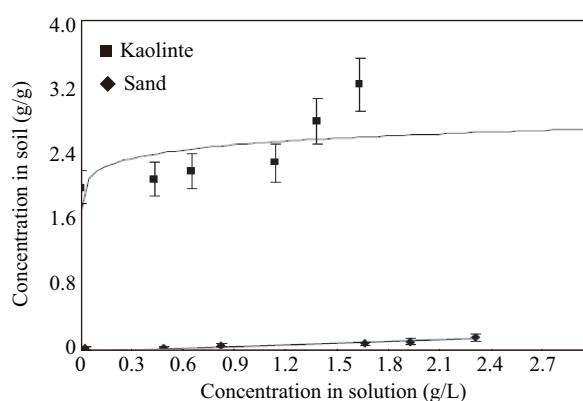
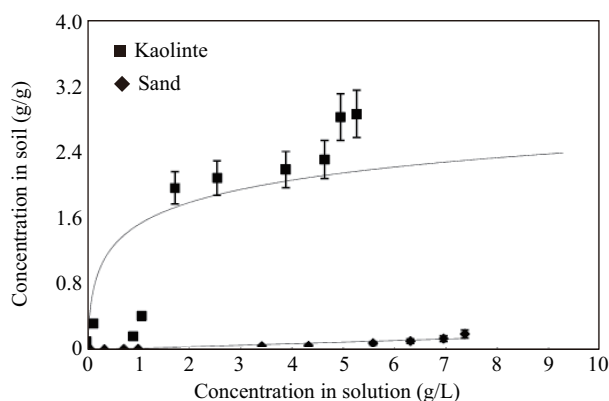
**Table 2** Adsorption isotherms and its coefficients

Surfactant	Soil	Equation
Triton X-100	Sand	$Y = \frac{0.083X}{1+2.89X}$
	Kaolinite	$Y = \frac{27.93X}{1+42.81X}$
Triton X-100 (with ionic strength)	Sand	$Y = \frac{0.08X}{1+1.21X}$
	Kaolinite	$Y = \frac{1.83X}{1+1.85X}$
CTAB	Sand	$Y = \frac{0.022X}{1+0.029X}$
	Kaolinite	$Y = \frac{0.16X}{1+0.016X}$
CTAB (with ionic strength)	Sand	$Y = \frac{0.01X}{1+0.001X}$
	Kaolinite	$Y = \frac{9.87X}{1+3.44X}$

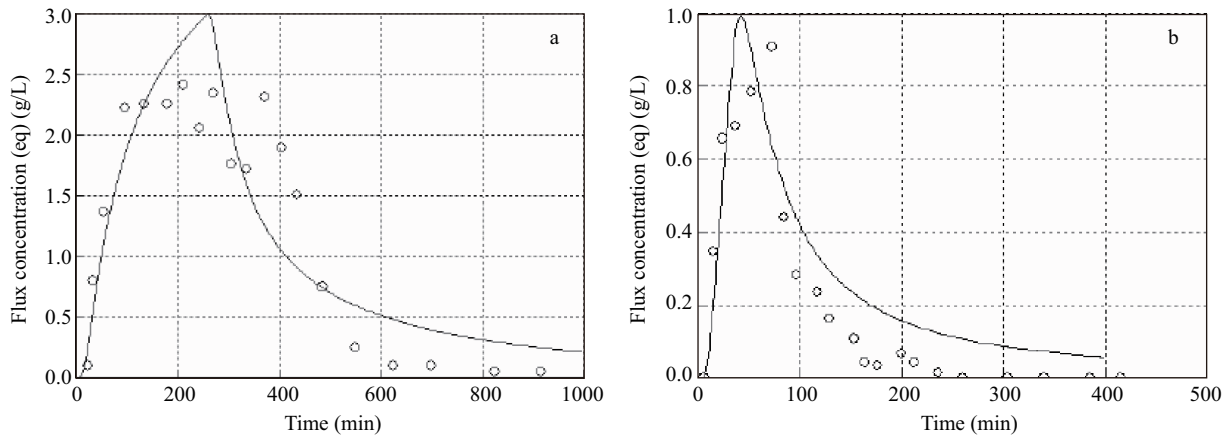
matrix grains must be considered. These interactions are qualitatively described by the DLVO theory (Derjaguin and Landau, 1941) and play an important role in the deposition of colloidal particles on sediment matrices. Laboratory experiments concerning the deposition rates of colloidal particles have been observed to be several orders of magnitudes larger than predictions based on the DLVO theory (Elimelech and O'Melia, 1990). This discrepancy may be a consequence of local roughness and variation of charge distribution at the surface of colloidal particles and sediment matrices. Thus, the interaction energy of a given particle may vary widely with position across these

surfaces. Due to the influence of parameters such as the ionic strength, the valence of the dominant counterion and the pH on colloidal particles and matrix grains must be considered, too (Elimelech and O'Melia, 1990).

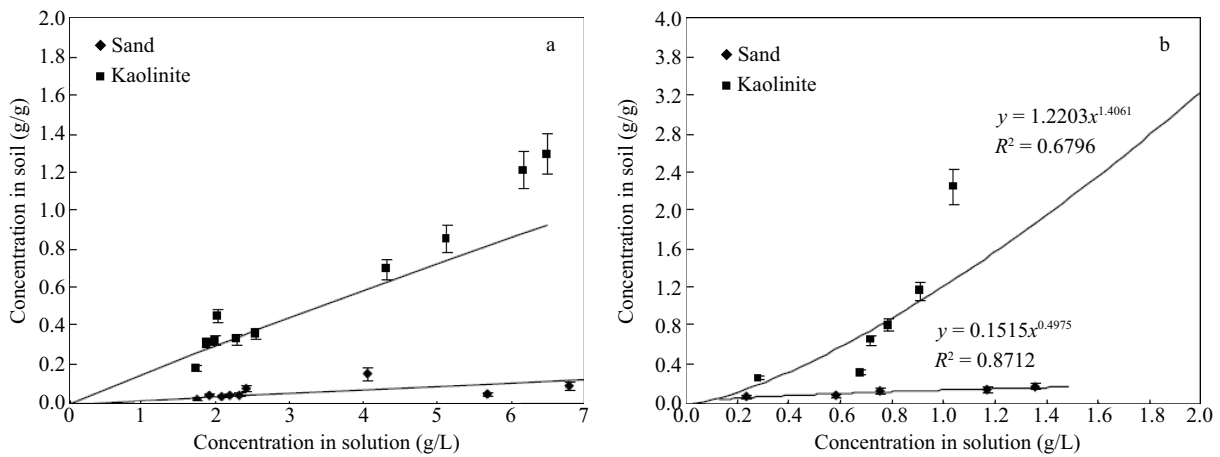
With increasing electrolyte concentration the electric double layer repulsion decreases resulting in a decreasing mobility of the colloidal particles. At very low salt concentrations, electric double layer interactions are very large, and deposition is expected to increase (Elimelech et al., 1995). This fact was observed from surfactant solutions breakthrough studies from column experiments. Before conducting column experiments, batch studies were

**Fig. 4** Triton X-100 adsorption in soil with ionic strength of 0.1 g/L.**Fig. 3** Triton X-100 adsorption (a) and desorption (b) in soil (batch study).**Table 3** Desorption of Triton X-100 and CTAB in soil

Soil	Langmuir	Linear	Freundlich
Triton X-100			
	Sand	$Y = \frac{2.67X}{1+0.089X}$ $R^2 = 0.45$	$Y = 0.070X$ $R^2 = 0.75$
Kaolinite	$Y = \frac{1250X}{1+2.43X}$ $R^2 = 0.28$	NA NA	$Y = 2.49X^{0.06}$ $R^2 = 0.43$
CTAB			
	Sand	$Y = \frac{0.23X}{1+0.27X}$ $R^2 = 0.96$	$Y = 0.15X$ $R^2 = 0.60$
Kaolinite	NA NA $R^2 = 0.95$	$Y = 1.35X$ $R^2 = 0.54$ NA	$Y = 1.22X^{1.41}$ $R^2 = 0.68$ $R^2 = 0.86$



**Fig. 5** Breakthrough curve of Triton X-100 in sand (82.5%) and kaolinite (17.5%) (a), and Triton X-100 in sand (82.5%) and kaolinite (17.5%) (0.1 g/L ionic strength) (b).

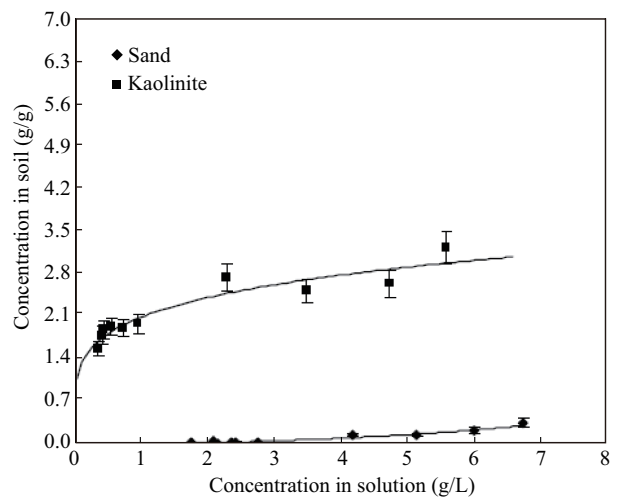


**Fig. 6** CTAB adsorption (a) and desorption (b) in soil (batch study).

done with NaCl electrolyte solution. The ionic strength had some influence in transportation of surfactants in soil. Triton X-100 retardation factor increased from 9.546 (Table 4) to 13.525 in sand kaolinite mixture. The above values indicate that the electrolyte solution has some impact in transportation of surfactant solutions in soil.

The retardation factor of CTAB in sand and kaolinite soil was 14.83 in pure surfactant solutions. With the addition of 0.1 g/L NaCl into the surfactant solutions, CTAB retardation factor ( $R$ ) increased to 21.09 in soils (Table 4, Fig. 11a, b). This follows the DLVO theory (Derjaguin and Landau., 1941) which is when the ionic strength increases, retardation factor increases. Diffusion coefficient of Triton X-100 decreased with the introduction of electrolyte solution. In case of CTAB, it is increased (Table 4).

The relationship between of seepage velocity ( $V$ ) and diffusion ( $D$ ) was correlated using linear relationship with good correlation ( $R^2 = 0.9354$ ). De Smedt and Wierenga (1979) found dispersion to be linearly related to seepage velocity ( $D = 1.2 + 0.021V$ ) for saturated and unsaturated columns. However, these studies were conducted on col-



**Fig. 7** Breakthrough curve of Triton X-100 in sand (82.5%) and kaolinite (17.5%) (a), and Triton X-100 in sand (82.5%) and kaolinite (17.5%) (0.1 g/L ionic strength) (b).

umn of glass beads and intact sandstone and therefore may not reflect the conditions present in soil, as glass beads represent a very uniform media and sandstone has few



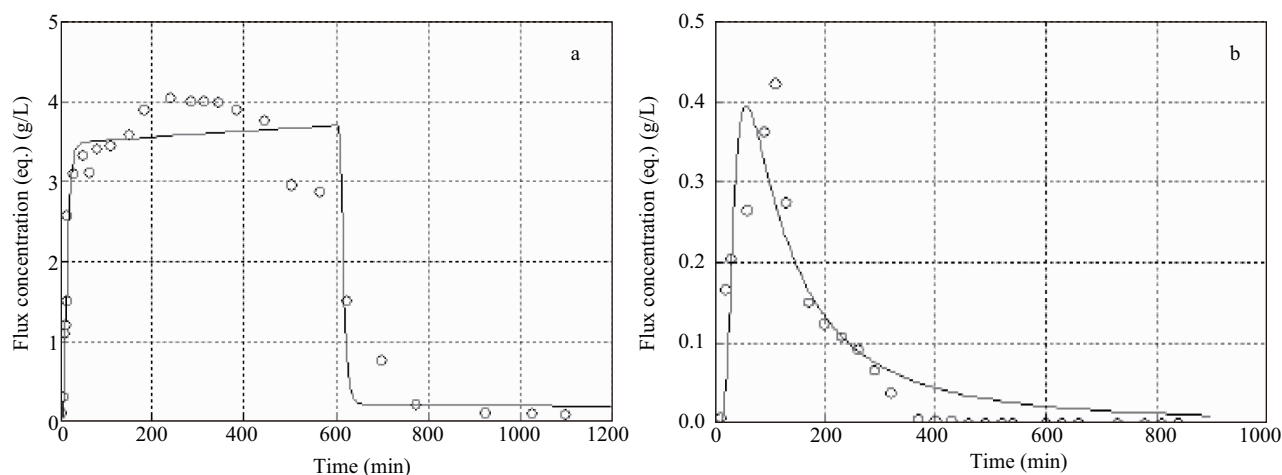
**Table 4** Transport parameters of Triton X-100 and CTAB in soil

Surfactant	Soil type	Parameter		RMS (root mean square)
		$D$ (cm <sup>2</sup> /min)	$R$	
Triton X-100	Sand (82.5%) and kaolinite (17.5%)	4.160	9.546	0.2875
	Sand (82.5%) and kaolinite (17.5%) with ionic strength	2.48	13.525	0.02528
CTAB	Sand (82.5%) and kaolinite (17.5%)	0.15	14.83	0.1541
	Sand (82.5%) and kaolinite (17.5%) with ionic strength	3.421	21.09	0.003203

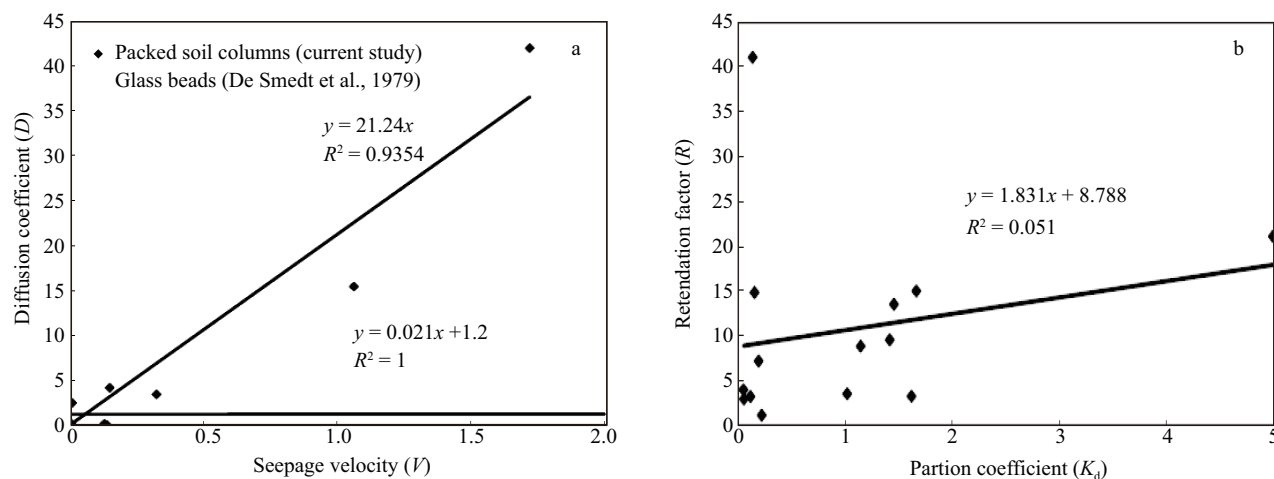
interconnecting pores. In sand column, dispersion is much higher than seepage velocity compared to glass beads Hutchison (2003). Our experiments derived the following relationship (Fig. 9a). Diffusion ( $D$ ) = 21.242 × Seepage velocity ( $V$ ). The relationship with retardation factor ( $R$ ) which is obtained from column studies and partition coefficient ( $K_d$ ) which is obtained from batch studies are shown in Fig. 10.  $K_d$  was measured from batch studies. There is a good correlation observed. The retardation factor for surfactant includes all of the interactions with the soil surfaces. These interactions tend to retard the migration of the surfactant relative to the water and delay its arrival downstream or down gradient. To model or

predict surfactant transport and plan remediation activities at a site, both hydrologic and chemical behaviors need to be known. Particle deposition coefficient  $K_d$  is one the parameters influencing the retardation factor.

Initially PCE was removed using water. Various surfactants were used to remove the remaining PCE. Triton X-100 had more removing capacity compared CTAB (Table 5). The surfactant aided clayey soil flushing system for chlorinated compounds has been proven useful in promoting overall soil washing performances. This is because the micellar solubilized surfactant has a positive effect in promoting the partition process and increasing the driving force for removing hydrophobic contaminants.



**Fig. 8** Breakthrough curve of CTAB in sand (82.5%) and kaolinite (17.5%) (near zero ionic strength) (a), and CTAB in sand (82.5%) and kaolinite (17.5%) (0.1 g/L ionic strength) (b).



**Fig. 9** Relationship of seepage velocity ( $V$ ) vs. diffusion coefficient ( $D$ ) (a), and retardation factor ( $R$ ) vs. partition coefficient ( $K_d$ ) (b).

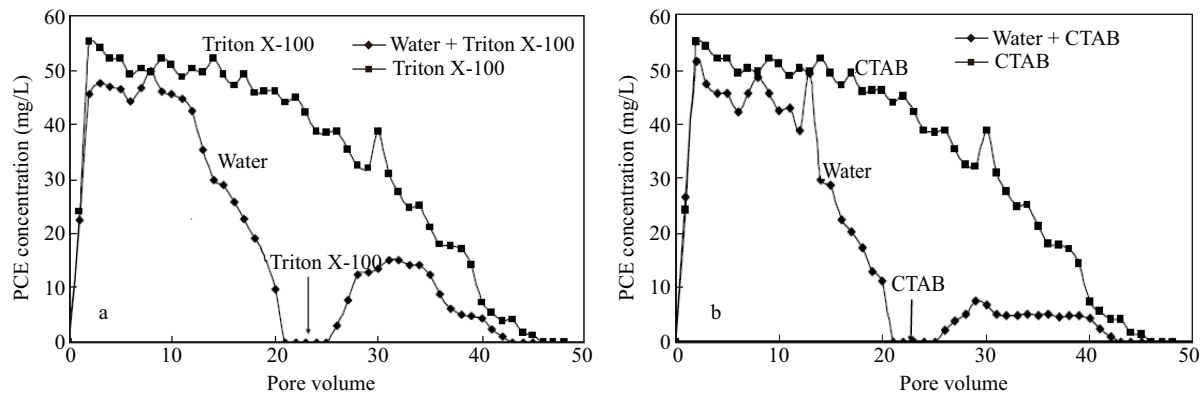


Fig. 10 PCE contaminated soil-water-Triton X-100 (a) and soil-water-CTAB (b) solutions breakthrough in sand (82.5%) and kaolinite (17.5%) mixture.

Table 5 PCE removed by flushing in sand-kaolinite soil

	Triton X-100	CTAB
Water	0.0357%	0.0353%
Water + surfactant	0.0770%	0.0395%
Surfactant	0.0913%	0.0787%

The soil washing performance depends on the surfactant's physicochemical properties, Triton X-100 being the better surfactant over CTAB because of its lower critical micelle concentration and the fact that less surface precipitation is involved, which results in a higher soil washing performances.

Depending on the surfactant and the properties of the PCE and soil, dispersion of the surfactant components into the PCE can have a potential impact on surfactant enhanced aquifer remediation. The high interfacial tensions between PCE and water result in large capillary forces and large displacement entry pressures that resist flushing by water. The surfactants should have for the solubilization of chlorinated compounds are: (1) low micro emulsion density to avoid vertical migration; (2) fast coalescence to prevent the formation of meta stable macro emulsions (3) low microemulsion viscosity to prevent PCE displacement and high head loss through media (4) high solubilization capacity to reduce the number of pore volumes needed to achieve the remediation goals and (5) high PCE microemulsion interfacial tension (IFT) to eliminate downward PCE migration. An additional screening parameter is compatibility between the surfactant and soil, including low surfactant absorption. Even though both Triton X-100 and CTAB solubilize less PCE on the basis of the experiments and simulations presented in this work, Triton X-100 has more potential in solubilizing PCE compared to that of CTAB.

### 3 Conclusions

In this study, the sorption and transport experiments of CTAB and Triton X-100 were conducted.

(1) The sorption parameters, type of isotherm of

surfactants in clayey soil, retardation factor ( $R$ ) and diffusion coefficient ( $D$ ) of both surfactant solutions were determined.

(2) Retardation factor ( $R$ ) of CTAB and Triton X-100 increased with the introduction of electrolyte solution. CTAB's diffusion coefficient ( $D$ ) was increased in sand-kaolinite soil with the introduction of electrolyte solution. But in the case of Triton X-100 it was reduced.

(3) The efficiencies of PCE removal of both surfactants were determined. Triton X-100 had more removing capacity compared CTAB.

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