

MICELLE–WATER PARTITIONING OF PHENANTHRENE IN AQUEOUS SURFACTANT SOLUTIONS

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Received 31 March 1998

Abstract. Nonpolar hydrophobic organic compounds (HOCs) exhibit low aqueous solubilities and partition readily onto natural organic matter in soils and sediments. Such sorption onto soils/sediments may decrease their mobility in the natural environment, and may limit their bioavailability. Therefore, soil washing applications for the removal of HOCs from contaminated soil have frequently failed to produce the desired effect. Similarly, although bioremediation shows much promise for the restoration of aquifers and groundwater contaminated with organic chemicals, the limited aqueous solubility and excessive partitioning of HOCs has been observed to impede their biodegradation. The use of surfactants has been suggested as a means for increasing the aqueous solubilities of HOCs and decreasing their soil-sorbed concentrations. In this study, the distribution of a model HOC, phenanthrene, between micellar and aqueous pseudophases is examined through laboratory solubilization tests, and the potential application of selected surfactants in remediation scenarios is evaluated. The surfactants used include a nonionic sorbitan polyethoxylate and anionic and cationic surfactants.

Key words: micellization, hydrophobic organic contaminants, phase partitioning, interfacial tension, HOC mobilization, facilitated transport.

INTRODUCTION

Subsurface contamination by sparingly soluble organic compounds is a complex process. These chemicals may exist as a separate phase in discrete droplets or “ganglia” that are trapped in soil pores, or individual compounds may adsorb onto soil particles. Bioremediation may be a cost-effective technology for the treatment of such soils. However, not much is known about the physico-chemical and biological mechanisms that control the rate of bioremediation. In

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particular, hydrophobic organic compounds (HOCs) and nonaqueous phase liquids (NAPLs) interact strongly with soil organic matter; consequently, the effectiveness of microbial treatment can be affected by the processes controlling substrate accessibility to microorganisms and phase partitioning between soil, NAPL, and aqueous phases. In other words, the dissolution rates of pure crystals, or the rates of desorption of soil-sorbed organic compounds may control their biodegradation. Investigations involving degradation of organic compounds with soils, clays, or silicate suggest that sorption of organic substrates either slows biodegradation, renders the compounds poorly accessible to microorganisms, or results in the compound being degraded at a rate proportional to the solution concentration only and independent of the mass sorbed (Efroymsen & Alexander, 1994; Luthy et al., 1997).

Phenanthrene ($C_{14}H_{10}$, molecular weight 178.15) was selected as the model HOC in this study: phenanthrene is a three-ring polycyclic aromatic hydrocarbon (PAH). PAHs are a class of ubiquitous environmental pollutants. They are neutral, nonpolar HOCs comprised of two or more fused benzene rings. Considerable attention has been given to their widespread distribution in the environment and their possible exposure to humans, because several of these compounds are recognized as chemical carcinogens. Besides their presence in petroleum, PAHs are formed during the incomplete combustion of almost any organic material and have been isolated from air, water, soil, food, and vegetation samples; some common sources are cigarette smoke, automobile exhaust, chimney soot, refuse burning, oil pollution, and industrial processes. Consequently, there is considerable interest in the degradation and detoxification of this group of chemicals. Microorganisms are important in the degradation of PAHs in terrestrial and aquatic ecosystems, and it is expected that bioremediation will be an effective technology for the remediation of sites contaminated with PAHs. However, as with other HOCs, not much is known about the physicochemical mechanisms that may control the rate of biodegradation of PAHs in environmental samples, and it is suggested that mass transfer limitations associated with the release of contaminants from the soil-waste matrix limit the rate of PAH removal from soil, rather than the explicit aqueous-phase biodegradation kinetics.

Surfactant addition has been suggested as an innovative technique for decreasing interfacial tension and phase partitioning of the HOCs in soil. Surfactants are amphiphilic in nature, i.e., each molecule possesses both a hydrophilic moiety and a hydrophobic portion. Because of their amphiphilic nature, surfactant molecules self-assemble into dynamic clusters called micelles. Micelle formation occurs above a critical concentration of surfactant monomers (CMC). Typical CMCs range from 0.1 to 10 mM. In an aqueous micelle, individual surfactant monomers are oriented with hydrophilic moieties in contact with the aqueous phase and hydrophobic parts forming the interior of aggregate. HOCs like the PAHs partition into the hydrocarbon-like core of surfactant

micelles resulting in enhanced aqueous solubilities. Aqueous surfactant solutions may conceivably be used either in soil washing techniques to facilitate removal of hydrophobic contaminants from soil, or in soil bioremediation efforts by increasing the bioavailability of HOCs. Two general mechanisms by which surfactants can enhance the removal of NAPLs/HOCs are by micellar solubilization and by reduction of interfacial tension.

In the past several years the body of knowledge on surfactant solubilization of HOCs from soils has grown immensely as part of the effort to develop its remediation application. More recently the interactions between surfactant micelles and monomers, soil, HOC, and the aqueous phase have come under scrutiny and models have been developed to describe the partitioning behavior (Edwards et al., 1991, 1994; Abriola et al., 1993; Park & Jaffé, 1993; Ouyang et al., 1995; Okuda et al., 1996; Shiao et al., 1996). Excessive surfactant losses due to sorption onto soil may pose a major impediment to their use in HOC mobilization application; surfactant toxicity constitutes another concern. The selection of appropriate surfactants is, therefore, an important consideration.

The experimental observations on the effect of surfactant addition on microbial degradation of HOCs are not always very consistent, nor has a general explanation been advanced for their influence. It has been suggested that the application of surfactants or emulsifying agents may decrease interfacial tension and/or assist solubilization of sorbed HOCs from soils, thereby making the HOCs more available for microbial degradation. Bury & Miller (1993) observed enhanced bacterial growth rate and increased rate of *n*-alkane consumption in aqueous solutions of nonionic surfactants. The degradation of fluoranthene by *Sphingomonas paucimobilis* EPA505 is enhanced in the presence of alkylphenol surfactant (Lantz et al., 1994). Successful solubilization of coal constituents by crude and purified *Candida bombicola* biosurfactant has been reported (Breckenridge & Polman, 1994). Another body of research exists indicating either no effect or adverse effects on microbial degradation of HOCs in the presence of surfactant (Laha & Luthy, 1992).

This paper presents results from the solubilization of phenanthrene in selected aqueous surfactant solutions. The solubilization effects are compared with surface tension data for the surfactant solutions to determine the nature of the solubilization process. Micellization was seen to account for most of the increased phenanthrene solubility.

MATERIALS AND METHODS

Chemicals

The three-ring PAH, phenanthrene ($C_{14}H_{10}$, molecular weight 178.15, reported aqueous solubility of 1.29 mg/L at 25°C) was selected as the model HOC compound. Phenanthrene was obtained from Aldrich Chemical Company, WI

(purity >96%). [^{14}C]-Radiolabeled phenanthrene was obtained from Sigma Chemical Company, St. Louis, MO, with a specific activity of 8.3 mCi/mmol and purity >98%.

The surfactants selected for use in this study include the nonionic polyoxyethylene sorbitan monolaurate (Tween 20), the anionic sodium dodecyl sulfate (SDS), cationic tetradecyl trimethyl ammonium bromide (TTAB), and nonionic 3-methyl ether (3-ME). These surfactants, obtained from Sigma Chemical Co., were analytical grade (with purities >95%) and were used as received without further purification. At room temperature Tween 20 and 3-ME exist as liquids while SDS and TTAB exist as solids. Surfactant solutions used in the solubilization tests were prepared in biochemical oxygen demand (BOD) dilution water (Standard Methods ..., 1989).

Surface tension experiments

Surface tension measurements to determine CMC values for the surfactants were performed with a du Nouy ring tensiometer (Fisher Scientific Tensiomat Model 21). Surfactant solutions of varying concentrations were prepared in BOD dilution water, and the surface tension of the air/water interface of each solution was measured. Surfactant concentrations are reported as volume percent for liquid surfactants and as mass percent for solid surfactants. The glassware and ring were cleaned with acetone between readings. Multiple testing of each surfactant solution was performed to ensure consistent readings and standard corrections were applied for ring geometry and temperature to report surface tension values. Surface tension measurements were plotted against the logarithm of surfactant concentration. The surfactant concentration at which the surface tension no longer decreases significantly with increasing surfactant concentration was taken as representing surfactant CMC.

Solubilization tests

Solubilization tests were performed using sterilized 125-mL glass Erlenmeyer flasks fitted with Teflon-lined screw caps. Radiolabeled techniques were employed to measure the extent of phenanthrene solubilized. To confirm analytical results from ^{14}C data, identical solubilization tests were set up for phenanthrene and selected surfactants, and soluble phenanthrene was analyzed by high performance liquid chromatography (HPLC).

For the radiolabeled solubilization tests, each flask was spiked with 0.5 mL of a mixture containing either approximately 1 mg or 10 mg nonlabeled phenanthrene (representing about 10 times or 100 times the aqueous solubility, respectively) and approximately 0.05 μCi ^{14}C -phenanthrene dissolved in methanol (corresponding to ~110,000 disintegrations per minute). Methanol was then

allowed to evaporate, following which 100 mL of varying surfactant solutions prepared in sterilized BOD dilution water was added to each flask. Surfactant solutions were prepared at, below, and above the CMC as determined from the surface tension measurements. During equilibration, the flasks were continuously agitated on orbital shakers at room temperature. In order to determine the length of the equilibration period, samples were collected and analyzed daily for a week. Results from these equilibration tests indicated that phenanthrene equilibration in aqueous systems was attained within the first three days. Subsequent solubilization tests employed a three-day equilibration period.

Following equilibration, samples were withdrawn in duplicate from each test flask, filtered through 0.2 μm Teflon syringe filters to eliminate any undissolved phenanthrene, and injected into 20-mL glass counting vials with 10 mL of Ecoscint liquid scintillation cocktail (National Diagnostics, Atlanta, GA). Filters were pre-saturated with the phenanthrene solution to minimize adsorption during sampling. The samples were analyzed for ^{14}C on a Beckman 3801 liquid scintillation counter (LSC) using H# quench-monitoring technique with automatic quench compensation and random coincidence monitoring. Analysis of ^{14}C -phenanthrene was taken as representative of the behavior of all the phenanthrene.

The experimental setup used for solubilization tests employing chromatographic analyses was similar to the solubilization tests described above except that no radiolabeled phenanthrene was added. Samples were filtered and analyzed with a Hewlett Packard HP 1090 liquid chromatograph using a Supelcosil 4.6-mm \times 15-cm LC-PAH column (Supelco, Bellefonte, PA) and a UV detector set at 254 nm. Sample dilutions were used where required. Conditions for HPLC analysis were as follows: 100 μL injection volume, 1 mL/min flow rate, gradient program with 95% water and 5% acetonitrile initially held for 2 min, and then going to 40:60 water/acetonitrile in 2 min. Calibration curves were prepared using phenanthrene standards prepared in methanol and analyzed under the same conditions without gradient using 40:60 water/acetonitrile as carrier.

Methanol was used as a solvent to prepare stock solutions of both radiolabeled and nonlabeled phenanthrene. This allowed for uniformity in the amount of phenanthrene added to each batch reactor and also enabled batch dosages of 10 to 100 times in excess of the aqueous solubility of phenanthrene. Excess phenanthrene is required to measure the progress of solubilization and make accurate estimates of molar solubilization ratios (MSR). Methanol was a preferred solvent because it showed no effect on surfactant solubilization, whereas most higher alcohols would affect CMC values significantly (Edwards et al., 1991). It was assumed that losses of phenanthrene during the evaporation of methanol would be insignificant because of the low volatility of this PAH. This assumption was borne out in the fairly complete mass balances on phenanthrene obtained at the conclusion of selected solubilization tests.

Mass balance

Mass balance evaluations were performed on selected samples prepared for both HPLC and LSC analyses at the end of the sampling period. The contents of each flask were extracted in 20 mL hexane by agitation for 15 min, followed by analysis of the hexane extract.

RESULTS AND DISCUSSION

All the surfactants tested were readily soluble in water and capable of increasing the aqueous solubility of phenanthrene significantly at concentrations above CMC except for 3-ME, which had no apparent effect on surface tension and therefore, no measurable CMC, up to a concentration of 5% by volume. Solubilization tests indicate that 3-ME did not increase the aqueous phase partitioning of phenanthrene at either concentrations examined. The following results were obtained in this experimental investigation.

Surface tension measurements

Surface tension data were examined through the construction of plots of surface tension versus the logarithm of surfactant concentration. The surface tension for each surfactant solution remained relatively constant at very dilute aqueous concentrations but decreased markedly with increasing surfactant concentrations for Tween 20, TTAB, and SDS. At higher surfactant concentrations, the surface tension again remains relatively constant: the sharp break signifying the onset of micelle formation, i.e., that CMC has been reached. Additional surfactant molecules no longer concentrate at the interface, but instead aggregate to form micelles.

Figure 1 shows the plot obtained for surface tension as a function of surfactant concentration for Tween 20 and is representative of the data obtained for TTAB and SDS. Tween 20 with the largest molecular weight was able to start forming micelles at a concentration of 0.01% (or ~ 100 mg/L) whereas TTAB and SDS required approximately 10 and 15 times this concentration. Surfactant concentrations close to the CMC may show a slight curvature due to surfactant inhomogeneities. The presence of polyoxyethylene chains of various lengths in a surfactant solution depresses the CMC to some extent. In the case of 3-ME, no CMC value was evident, perhaps because of the small size of its hydrophilic and hydrophobic groups. Temperature had no significant impact on surface tension measurements, and the data presented in Fig. 1 are averages for measurements at different temperatures.

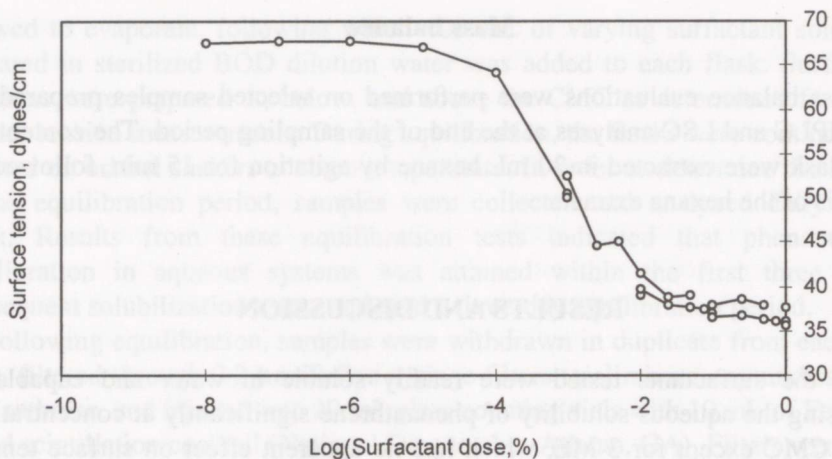


Fig. 1. Surface tension measurements for aqueous Tween 20 solutions.

Table 1 shows CMC values estimated from surface tension data, as well as values reported in the literature. In general there is good agreement in CMC values obtained from surface tension measurements and those reported in the literature. Also listed in Table 1 are the surfactant concentrations at which the solubilization of phenanthrene is initiated.

Table 1

Properties of selected surfactants

Surfactant	Molecular weight	CMC, %		Surfactant dose for solubilization, %	
		from literature	from surface tension measurements	HPLC	LSC
Polyoxyethylene sorbitan monolaurate (Tween 20) <i>nonionic</i>	1225	0.01 (100 mg/L)	0.01 (100 mg/L)	0.01 (100 mg/L)	0.015 (150 mg/L)
Sodium dodecyl sulfate (Lauryl sulfate or SDS) <i>anionic</i>	288.4	0.24 (2400 mg/L)	0.16 (1600 mg/L)	0.12 (1200 mg/L)	0.17 (1700 mg/L)
Tetradecyl triammonium bromide (TTAB) <i>cationic</i>	336.4	0.15 (1500 mg/L)	0.1 (1000 mg/L)	0.08 (800 mg/L)	0.10 (1000 mg/L)
3-Methyl ether (3-ME) <i>nonionic</i>	164.2	N/A	N/A	N/A	N/A

N/A = not available.

Phenanthrene solubilization

Initially kinetic studies were performed to determine the equilibration period required for micellar solubilization of phenanthrene. For these tests, phenanthrene concentrations in the aqueous pseudophase were monitored daily for several days while continuously agitating the surfactant solutions. Measured phenanthrene solubilities at different sampling times were compared. Equilibration was deemed complete when the extent of phenanthrene solubilization was no longer a function of reaction time. The required equilibration period was determined to be less than three days.

Phenanthrene solubilization was studied as a function of the surfactant dose for the selected surfactants. Figure 2 shows the solubilization of phenanthrene by Tween 20 as a plot of apparent phenanthrene solubility versus surfactant dose. Comparison of solubilization data obtained by HPLC analysis and radiolabeled techniques shows fairly good agreement between the analytical methods. Solubilization results for Tween 20 indicate that at surfactant concentrations less than CMC there is no significant change in the apparent solubility of phenanthrene, which remains around 1 mg/L. Significant increases in phenanthrene solubility occur at Tween 20 concentrations greater than CMC. Apparent phenanthrene concentrations of 10 times its aqueous solubility could be achieved at supra-CMC surfactant doses: essentially all the phenanthrene added to the aqueous system is solubilized. Similar solubilization results were

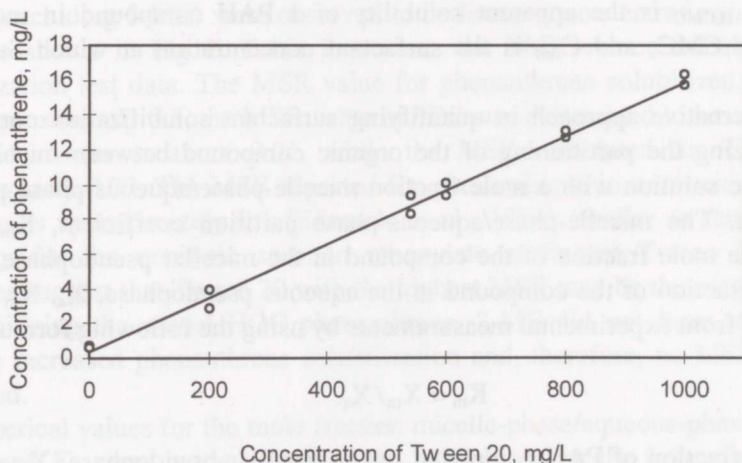


Fig. 2. Phenanthrene solubilization in aqueous Tween 20 solution.

obtained for TTAB and SDS. These results indicate that the observed solubilization of phenanthrene is a micellar phenomenon representing the partitioning of phenanthrene into surfactant micelles. No enhanced solubilization was observed for 3-ME, even with surfactant concentrations up to 1500 mg/L. These results are supported by surface tension measurements which indicate no measurable CMC at concentrations up to 5% (or 50,000 mg/L).

Modeling phenanthrene partitioning

Edwards et al. (1991) have presented a comprehensive model for the solubilization of HOCs in aqueous surfactant solutions. Their model assumes the existence of two phases: the aqueous pseudophase and the micellar pseudophase. The effectiveness of a particular surfactant in solubilizing a given HOC solubilize (in this case, phenanthrene) can be determined from the MSR (Kile & Chiou, 1989). MSR is the number of moles of organic compound solubilized per mole of micellar surfactant in solution. In the presence of excess HOC, the MSR may be determined from the supra-CMC slope of the curve that results when the solubilize concentration is plotted against surfactant concentration.

The MSR for solubilization of PAH compounds may be calculated as follows:

$$MSR = (S_{PAH,mic} - S_{PAH,CMC}) / (C_{surf} - CMC), \quad (1)$$

where $S_{PAH,mic}$ is the total apparent solubility of the PAH compound in moles per liter in micellar solution at a particular surfactant concentration greater than the CMC; $S_{PAH,CMC}$ is the apparent solubility of a PAH compound in moles per liter at the CMC; and C_{surf} is the surfactant concentration at which $S_{PAH,mic}$ is evaluated.

An alternative approach in quantifying surfactant solubilization consists of characterizing the partitioning of the organic compound between micelles and monomeric solution with a mole fraction micelle-phase/aqueous-phase partition coefficient. The micelle-phase/aqueous-phase partition coefficient, K_m , is the ratio of the mole fraction of the compound in the micellar pseudophase, X_m , to the mole fraction of the compound in the aqueous pseudophase, X_a . K_m may be calculated from experimental measurements by using the following formula:

$$K_m = X_m / X_a. \quad (2)$$

The mole fraction of PAH compound in the micellar pseudophase, X_m , may be calculated as

$$X_m = (S_{PAH,mic} - S_{PAH,CMC}) / (C_{surf} - CMC + S_{PAH,mic} - S_{PAH,CMC}) \quad (3)$$

or in terms of the MSR, as:

$$X_m = \text{MSR}/(1 + \text{MSR}). \quad (4)$$

The mole fraction of PAH in the aqueous pseudophase, X_a , is approximated for dilute solutions by

$$X_a = S_{\text{PAH,CMC}} V_w, \quad (5)$$

where V_w is the molar volume of water, e.g., 0.01805 L/mol at 25 °C. Thus, the following expression for K_m is derived:

$$K_m = (S_{\text{PAH,mic}} - S_{\text{PAH,CMC}})/[(C_{\text{surf}} - \text{CMC} + S_{\text{PAH,mic}} - S_{\text{PAH,CMC}})(S_{\text{PAH,CMC}} V_w)]. \quad (6)$$

MSR and micelle/water partitioning for phenanthrene

The mass of the surfactant added in excess of the CMC results in an increased micelle concentration, thereby providing a larger volume of hydrophobic micellar pseudophase available for phenanthrene solubilization. The extent of phenanthrene partitioning per micelle remains effectively constant above CMC; however, the number of micelles increases with surfactant concentration, facilitating micellar solubilization. Micellar solubilization is characterized by MSR, which is determined by the slope of the linear portion of the apparent solubility curve at surfactant concentrations above CMC. The MSR reflects the capacity of 1 mole of a particular surfactant in micelle form to accommodate a given HOC solubilize. The slopes of all apparent phenanthrene solubility curves (excluding 3-ME) were observed to be linear at concentrations above the CMC as shown in Fig. 2. Table 2 presents the MSR values calculated from solubilization test data. The MSR value for phenanthrene solubilized in Tween 20 is approximately 0.1, the MSR value in SDS was determined to be an order of magnitude lower at about 0.01, while the MSR calculated for TTAB was approximately 0.02. The MSR reported for phenanthrene in nonionic surfactant solutions is approximately 0.1 (Edwards et al., 1994), similar to that obtained currently for the nonionic sorbitan ethoxylate surfactant Tween 20. These estimates suggest that Tween 20 with the highest MSR may be the most effective at solubilizing the model HOC phenanthrene. 3-ME did not form micelles or produce increased phenanthrene solubilization and, therefore, no MSR value is presented.

Numerical values for the mole fraction micelle-phase/aqueous-phase partition coefficient, K_m , may be derived from the MSR by using the following formula (Edwards et al., 1994):

$$K_m = (55.4/S_{\text{PAH,CMC}}) [\text{MSR}/(1 + \text{MSR})]. \quad (7)$$

Similar calculations were performed in this study to yield values for micelle/water partition coefficients for the above three surfactants. The parameter K_m represents organic compound partitioning between nonpolar and polar pseudophases and is, therefore, specific for the solubilized compound, i.e., phenanthrene. Table 3 lists $\log K_m$ values calculated for phenanthrene solubilized in selected surfactants: the $\log K_m$ for phenanthrene in Tween 20 was about 6.3, $\log K_m$ for SDS ~ 5.3 and for TTAB ~ 6 . The literature reports $\log K_m$ of phenanthrene ~ 5.6 in nonionic surfactants.

Table 2

Molar solubilization ratios for phenanthrene in various surfactant systems

Equilibration period (days)	Tween 20	SDS	TTAB
Phenanthrene analysis by LSC			
3	0.1115	0.0115	0.0194
5	0.1019	0.0133	0.0217
>7	0.1012	0.0137	0.0160
Phenanthrene analysis by HPLC			
3	0.0977	0.0071	0.0266
5	0.0998	0.0108	0.0244
>7	0.0991	0.0104	0.0215

MSR values computed as the slope of the linear part of the solubilization curves, and presented at different equilibration times. Two different analytical techniques were used to measure phenanthrene concentration. MSR for phenanthrene in nonionic surfactant solutions was reported as ~ 0.1 . Phenanthrene added corresponded to $10\times$ aqueous phenanthrene solubility.

Table 3

Experimentally determined $\log K_m$ values from MSR calculations

Equilibration period (days)	Tween 20	SDS	TTAB
Phenanthrene analysis by LSC			
3	6.1551	5.2204	5.8023
5	6.3434	5.1857	5.7693
>7	6.2092	5.5236	5.9184
Phenanthrene analysis by HPLC			
3	6.1708	5.0518	6.6230
5	6.5143	5.1095	6.0546
>7	6.1024	5.3207	6.2398

Relationship between K_m and MSR defined earlier was used to compute K_m values. Literature-reported value for $\log K_m$ of phenanthrene is ~ 5.6 in nonionic surfactants. Micelle/water partition coefficients are presented as $\log K_m$ values.

Mass balance

Mass balance analyses performed on batch reactors prepared with Tween 20 using HPLC and LSC analyses indicated phenanthrene recovery efficiencies 67–90% and 93–112%, respectively. In the case of TTAB, the phenanthrene recovery efficiencies were between 76–90% and 95–105%, respectively, for HPLC and LSC. These results suggest satisfactory mass balances for phenanthrene when analyzing by radiolabeled techniques (LSC). Although recovery efficiencies were slightly lower for analysis by HPLC methods, the data are still acceptable for the confirmatory purposes designed.

CONCLUSIONS

The apparent solubility of phenanthrene was measured in nonionic, cationic, and anionic surfactant solutions. In the presence of excess phenanthrene, the solubility of phenanthrene increased linearly with surfactant dose at surfactant concentrations in excess of CMC. Essentially all the phenanthrene added was solubilized at higher surfactant doses yielding apparent aqueous solubilities of >14 mg/L (corresponding to 10× aqueous phenanthrene solubility of 1.3 mg/L). Comparison of the surface tension data with results from solubilization tests indicates that solubilization of phenanthrene by Tween 20, SDS, and TTAB occurs only at supra-CMC surfactant concentrations and is, therefore, a micellar phenomenon. 3-ME produced no phenanthrene solubilization at concentrations tested.

The slopes obtained from Tween 20, SDS, and TTAB solubilization data were used to determine MSR and micelle/water partition coefficients, K_m . MSR and K_m are used to characterize solubilization of HOCs in micellar solution, higher values indicate better solubilizing ability. Results indicate that the nonionic sorbitan ethoxylate surfactant Tween 20 may be the most effective solubilizing agent. This conclusion is supported by earlier research reports.

This work was confined to evaluating the surfactant solubilization of phenanthrene in batch systems that received only the PAH, surfactant, and water. In the presence of soil, it is expected that significantly higher surfactant concentrations will be required to produce commensurate HOC solubilization because of surfactant sorption onto soil. Therefore, in any remediation scenario involving soil washing or surfactant-enhanced bioremediation, considerably greater surfactant additions would be required to ensure micellar solubilization. In addition, it would be necessary to ensure that the addition of surfactant and the presence of solubilized HOC do not create a potential contamination problem and do not produce any inhibitory or toxic effects on microorganisms to be used in biologically treating the contaminated media.

ACKNOWLEDGEMENTS

We express our appreciation of Mehrzad Mehran and Nahid Golkar for their assistance in developing analytical methods. Funding for this research was provided by the University of Michigan, Michigan State University, and Howard University through the Great Lakes Mid-Atlantic Center for Hazardous Substance Research under Grant R-819605 from the Office of Research and Development, U.S. Environmental Protection Agency. Partial funding of the research activities of the Center was also provided by the State of Michigan Department of Natural Resources. The content of this publication does not necessarily represent the views of any of the funding agencies.

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FENANTREENI JAOTUMINE MITSELLI JA VEE PIIRPINNAL PINDAKTIIVSE AINE VESILAHUSES

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On käsitletud mittepolaarsete orgaaniliste ühendite jaotumist mitselli ja vee vahel pindaktiivsete ainete vesilahuses. Laboratoorsete uuringutega on näidatud, et fenantreeni liia korral suureneb fenantreeni lahustuvus lineaarselt pindaktiivse aine hulga suurenemisega. On antud soovitused pindaktiivsete ainete kasutamiseks mittepolaarsete ühenditega saastunud pinnaste puhastamisel.