A novel solubilization of phenanthrene using Winsor I microemulsion-based sodium castor oil sulfate

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Abstract

Problems associated with polycyclic aromatic hydrocarbons (PAHs) contaminated site in environmental media have received increasing attention. Ex situ soil washing is commonly used for treating contaminated soils by separating the most contaminated fraction of the soil for disposal. Surfactant-enhanced soil washing is being considered with increasing frequency to actually achieve soil-contaminant separation. In this research, a novel solubilization of phenanthrene and extraction of phenanthrene from spiked soil by sodium castor oil sulfate (SCOS) microemulsion was presented and compared with the conventional surfactants, Triton X-100 (TX100), Tween 80 (TW80), Brij35, sodium dodecylbenzene sulfonate (SDBS) and sodium dodecyl sulfate (SDS). Unlike conventional surfactants, SCOS forms stable microemulsion in water and thus behaves much like a separate bulk phase in concentrating organic solutes. The extent of solubility enhancement is linearly proportional to the concentration of SCOS microemulsion, in contrast with the effect of a conventional surfactant in which a sharp inflection occurs in the vicinity of the measured critical micelle concentration. SCOS microemulsion exhibits the largest mass solubilization ratio among the selected surface active agents (SAAs) in both soil-free system and soil–water system. The partitioning coefficients of phenanthrene between the emulsified phase and the aqueous phase, K_{em}, is slightly larger than those between the micellar pseudo phase and the aqueous phase, K_{mc}. The extraction experiments demonstrate high and fast desorption of phenanthrene from spiked soil by SCOS microemulsion perhaps due to its high solubilization capacity compared with the conventional surfactant solutions. The results show that SCOS could be an attractive alternative to synthetic surfactants in ex situ washing for PAH-contaminated soils.
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Keywords: Surfactant; Microemulsion; Phenanthrene; Solubilization; Soil washing

1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) in soils and aquifers may pose risks to the environment and human health. Because of the hydrophobic nature of PAH compounds, conventional remedies such as pump-and-treat have been proven to be of limited practical value [1,2]. Soil washing (ex situ

treatment of contaminated soils) also suffers from relatively poor soil-contaminant separation. Therefore, significant efforts are being devoted to the development of efficacious approaches for the remediation of these contaminated sites.

Surfactant may be beneficial for use in soil washing or soil-flushing pump-and-treat which spawned a great deal of interest in surfactant-enhanced remediation (SER) processes that has continued up to the present [3–11]. Typically, soil washing involved some mechanical energy addition (such as mixing) and in situ flushing involved only surfactant–contaminant interaction without adding external energy. Surfactant enhanced ex situ soil washing can

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offer the convenience, efficiency and economy desirable for innovative and alternative soil washing technologies. The main factors that should be considered when selecting surfactant include effectiveness, cost, public and regulatory perception, biodegradability and degradation products, toxicity to humans, animals and plant, and ability to recycle. The first consideration is that the surfactants are efficient in removing the contaminants. Under these requirements, anionic surfactant, ethoxylated nonionic surfactant, cyclodextrins [12], humic acids [13], natural surfactant [14] and biosurfactant [15] were used to improve the solubilization and bioavailability of PAHs. However, microemulsion e.g., oil-in-water (Winsor I type) microemulsion may be a potential approach for the remediation of soils and groundwater due to its high solubilization capacity relative to the surfactant micellar solutions [16].

Since Schulman introduced the term "microemulsion" in 1959, microemulsions have attained increasing significance both in basic research and industrial applications [17]. Recently, much attention has been paid to its application in SER. Martel et al. [18,19] optimized different surfactant–alcohol–solvent microemulsions to recover DNAPLs from sand columns. Although high recovery was obtained from these studies, the solvent components, i.e., toluene, xylene, ethylbenzene, etc. would risk in contaminating the soils and groundwater. A ternary microemulsion of water-rapeseed oil-polyglycoside (APG) significantly extracted pyrene (Py) from a real soil sample, and its ingredients (APG and rapeseed oil) are biodegradable [17]. However, 10% (wt. fraction) of APG would be of a great cost for the cleanup of contaminated soils.

The commercial sodium castor oil sulfate (SCOS) (Turkey red oil) is manufactured by treating natural castor oil with sulfuric acid and is used as a emulsifying and dispersing agent in industrial applications [20]. SCOS is a mixture of free castor oil, sodium castor oil sulfate, sodium castor oil acid, inorganic salts and water, etc. The structures of main ingredients are shown in Scheme 1. SCOS is aptitude for biodegradation due to the unsaturated bonds and hydroxyl groups in the structures of its ingredients. A stable microemulsion (oil-in-water) or swollen micellar solution forms when SCOS is mixed in water. Most conventional surfactants are derived from petroleum hydrocarbons (non-reproducible resources). However, SCOS is a ramification of the reproducible castor oil. The objectives of the present study are: (1) to compare the solubilization capacity of SCOS for phenanthrene with the synthetic surfactants, Triton X-100 (TX100), Tween 80 (TW80), Brij35, sodium dodecylbenzene sulfonate (SDBS) and sodium dodecyl sulfate (SDS), which have been extensively used in laboratory and field remediation study; and (2) to compare the extraction efficiency of phenanthrene from spiked soil by SCOS microemulsion with the conventional surfactant solutions. This study explores the potential of SCOS microemulsion in ex situ washing for PAH-contaminated soils.

Table 1
Characteristics of the selected surfactants

Surfactant	Molecular formula	Molar weight (g/mol)	CMC[a] (mg/L)
TX100	$C_8H_{17}C_6H_4(OCH_2CH_2)_{9.5}OH$	625	167.4
TW80	$C_{17}H_{35}COOS_6{}^*(OCH_2CH_2)_{20}OH$	1309	73.36
Brij35	$C_{12}H_{25}(OCH_2CH_2)_{23}OH$	1200	65.71
SDBS	$C_{12}H_{25}C_6H_4SO_3Na$	348.48	963.2
SDS	$C_{12}H_{25}OSO_3Na$	288.38	1586

$S_6{}^*$: a sorbitan ring $-C_6H_{11}O_4-$.
[a] The critical micelle concentration measured in this work.

2. Experimental section

2.1. Materials

Sodium castor oil sulfate is of experimental grade, obtained from Shanghai Chemical Company, China and used as received. The bulk material was dark yellow and high viscous liquid. The content of water and inorganic salts were measured as 13.44 and 1.87%, respectively, by the weight analysis [21]. A stock solution at concentration of 100 g/L was prepared which was based on the mass of raw material. At ambient temperature, the solution at concentrations greater than 1000 mg/L show slight turbidity. At concentrations lower than 500 mg/L, the opalescence of the solutions is not apparent. The pH of SCOS solution varies from 6.5 to 7.0. Phenanthrene (purity $\geq$ 98%) was purchased from Aldrich, TX100 was obtained from Sigma and SDS (purity $\geq$ 98%), TW80 and Brij35 were purchased from Acros Organics, respectively. SDBS (purity $\geq$ 98%) was purchased from Tokyo Kasei Kogyo Co. Ltd. The characteristics of the selected surfactants are given in Table 1. Methanol and acetone were obtained as analytical grade solvent. Purified water was used for all tests.

2.2. Material preparation

A vadose zone soil collected from Hangzhou, China was air-dried and sieved through a 0.28-mm sieve. The soil had a pH of 5.05 and organic matter of 1.45%. This PAH-free soil was then spiked with phenanthrene dissolved in acetone. The acetone was evaporated under hood, and the spiked soils with phenanthrene contamination were mixed and homogenized. The initial concentration was 197.3 mg phenanthrene/kg soil.

2.3. Characterization of SCOS microemulsion

2.3.1. Measurement of surface tension and CMC

Surface tension of surfactant solutions were measured by using a Model 20 tensionmeter (Fisher Science Instrument Co., USA). This instrument operates on the DuNouy principle in which a platinum ring is suspended from a torsion balance and the force (in mN/m) necessary to pull the ring free from the surface film is measured. The critical micelle concentration (CMC) was determined by measuring the surface tension versus surfactant concentration; the plotted surface
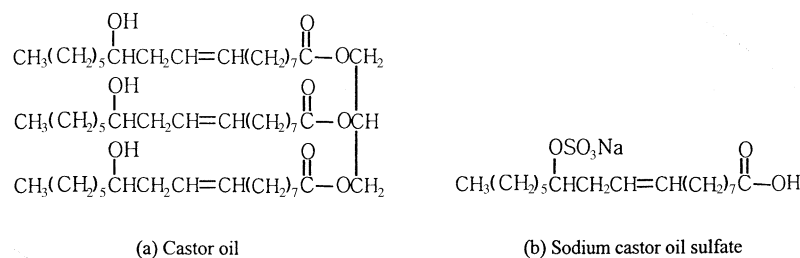
Scheme 1. Structures of (a) castor oil and (b) sodium castor oil sulfate.

tension value was taken when stable reading was obtained for a given surfactant concentration, as indicated by at least three consecutive measurements having nearly the same value. The CMC values were obtained through a conventional plot of the surface tension versus the logarithm value of the surfactant concentration.

2.3.2. Centrifugation

Freshly prepared 1000, 5000 and 10,000 mg/L of SCOS solutions, placed for 1, 3, 6 and 12 months or mixed with K_2SO_4 (100 mmol/L), respectively, were transferred into 25-mL Corex centrifuge tubes and centrifuged for 1 h at 2987g of the relative centrifuge force (RCF) on a Model Biofuge Prima R centrifuger (Hanau, Germany) to test if phase separation occurred.

2.4. Batch solubilization and extraction procedures

The solutions of surface active agents (SAAs), i.e., SCOS, TW80, TX100, Brij35, SDBS and SDS at different total concentrations were prepared, respectively, in flasks. To test the intrinsic solubilization extent in soil-free system and the apparent solubilization extent in soil–water system, 0.0, 1.0 and 2.0 g of phenanthrene-free soil was added into 25-mL Corex centrifuge tubes with Teflon cap liners and then a series of 20 mL of SAA solutions were placed into it. Phenanthrene was added in an amount slightly more than required to saturate the solution. Duplicate samples and controls without phenanthrene addition were prepared for each concentration solution; these samples and controls were then equilibrated on a reciprocating shaker for 48 h at $25 \pm 1\,^{\circ}$C. (Previous experimental results showed 48 h mixing time to be sufficient for obtaining equilibrium solubilization under mixing conditions). The samples were subsequently centrifuged for 1 h at the speed of 5000 rpm (2987g). An appropriate aliquot of the supernatant was then carefully withdrawn with a volumetric pipette and diluted to 10 mL in flasks with 4.0 mL of methanol and the rest of water. The absorbency of diluted samples was measured at 250.8 nm on Model UV2401PC spectrophotometer (Shimadzu, Japan) with a 1.0 cm cell. The absorbency difference between sample and control was calculated and phenanthrene was quantified from the calibration.

Batch soil washing studies were conducted by placing a constant ratio of soil to SAA solution while the extraction efficiency was evaluated. A series of 1.0 g of phenanthrene-

spiked soil was added into centrifuge tubes and 20 mL of 500 mg/L SAA solutions was placed into it. The controls were prepared using phenanthrene-free soil. These samples and controls were then reciprocately shaken. At the set time intervals, the sample and the control were taken out and centrifuged. The phenanthrene in supernatant was quantified as above and the extraction efficiency was evaluated from the amount of phenanthrene in initial soil and water.

The calibration was obtained by diluting the standard phenanthrene solution to 10 mL in flasks with methanol and water, measuring the absorbency at 250.8 nm on spectrophotometer with a 1.0 cm cell. The regression results of calibration were: $A = 0.3614C$ (mg/L), $n = 6$, $R^2 = 1.000$, $\varepsilon = 6.44 \times 10^4$ L/(mol cm). The interferences from 200 mg/L of SCOS, TX100, TW80, Brij35, SDBS and SDS on the reading of 1 mg/L of phenanthrene were -2.12, -0.83, -1.98, -1.10, -2.05 and -1.67%, respectively.

3. Results and discussion

3.1. Characterization of SCOS microemulsion

Fig. 1 shows a plot of the surface tension as a function of log SAA concentration at room temperature. No distinct inflection was detected in the plot with SCOS concentration extended to 5000 mg/L, while a break point was observed for the conventional surfactant solutions, e.g., for TX100 and
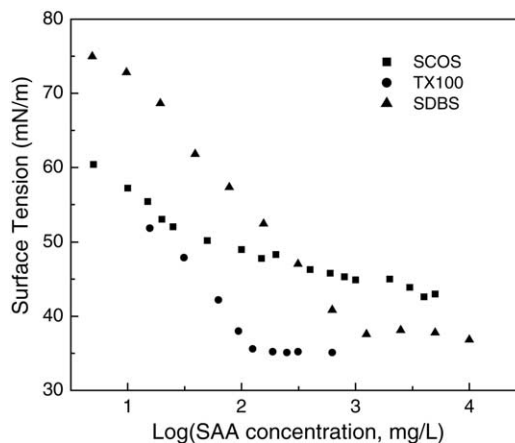

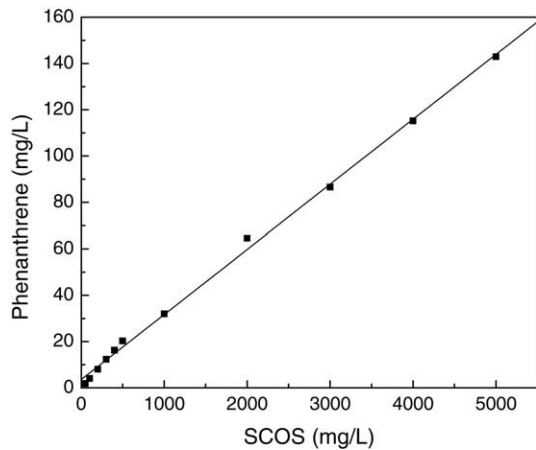Fig. 1. Surface tension vs. the log SAA concentrations.

Fig. 2. Solubilization of phenanthrene by SCOS microemulsions (soil-free).

SDBS, respectively, in Fig. 1, which indicates SCOS solutions behave differently from the micelle solutions. It is considered that a dispersing water–oil–surfactant system, with transparent or semi-transparent appearance and high mobility, is a microemulsion if no phase separation occurs after it is centrifuged at $100 \times g$ of the RCF for 5 min [22]. SCOS solutions were centrifuged at $2987 \times g$ of the RCF for 1 h. No phase separation was observed. The quiescent samples at the ambient conditions were allowed for 1, 3, 6 and 12 months and centrifuged, no phase separation was observed. However, when the solutions mixed with K_2SO_4 (100 mmol/L) were centrifuged, phase separation was observed with light-yellow oil floating and white precipitate sinking. These results illustrated that SCOS systems were stable microemulsions formed mainly by free castor oil (oil), SCOS (surfactant) and water. This microemulsion is termed as Winsor Type I, i.e., oil-in-water consecutive phase microemulsion.

The impacts of common cations in soil (such as Na^+, Ca^{2+}, NH_4^+, Mg^{2+} and K^+, respectively) on the phase separation of SCOS solutions were also tested. It was indicated that single cation such as Na^+, NH_4^+ and K^+ at concentrations less than 50 mmol/L caused no separation at 25 °C, while single Ca^{2+} and Mg^{2+} at concentrations more than 2.0 mmol/L did. It should be pointed out that no phase separation was observed after SCOS solutions were placed in refrigerator at about 5 °C for one year and centrifuged.

3.2. Solubilization and partitioning of phenanthrene

The relationships of the apparent phenanthrene solubilities as a function of SCOS concentrations in soil-free system at 25 ± 1 °C are shown in Fig. 2. The expressed SCOS concentration has not been corrected for the amount of water in the reagent. A linear relation is observed between the apparent phenanthrene solubility and SCOS concentration. The emulsified SCOS system is much like a separate bulk phase throughout the range of SCOS concentrations. This is in contrast to the behavior of a conventional (micelle-forming) surfactant that shows a distinct inflection in the solubility en-

hancement plot in the vicinity of the measured CMC [4]. This relation is consistent with the surface tension versus log SCOS concentration curve that shows no inflection, indicating the absence of monomer-micelle characteristics. The linear solubility enhancement of phenanthrene by SCOS microemulsions can be accounted for by the partition equilibrium of solute between the emulsified phase and the aqueous phase in analogy to the enhancement effect by dissolved natural humic substances [13,23] which can be expressed as:

$$S_w^* = S_w(1 + XK_{em}) \tag{1}$$

where S_w^* is the apparent solubility in water, S_w is the intrinsic water solubility of the solute (phenanthrene $S_w = 1.18$ mg/L, 25 °C, ref. [24]), X is the concentration of SCOS microemulsion (on a water-free basis), and K_{em} is the partition coefficient of solute between the emulsified phase and the aqueous phase. With the quantity of X expressed in g/mL in the solution and solute concentration in both water and emulsified phase expressed in the same weight-to-weight basis, the resulting K_{em} is a dimensionless quantity. Thus, the K_{em} value can be calculated from the slope and the intercept of the plot. The mass solubilization ratio (SR) of SCOS is defined as:

$$SR = \frac{S_w^* - S_w}{X} \tag{2}$$

Since surfactant cost will correspond to the mass of surfactant purchased, solubilization results are discussed in terms of absolute surfactant concentration. To compare the partitioning and the solubilization efficacy, the mass solubilization ratio (SR) and the micelle-phase/aqueous-phase partition coefficient (K_{mc}) are introduced which are the measures of the effectiveness of a particular surfactant in solubilizing a given solute. The SR is defined as:

$$SR = \frac{S_{PAH, mic}^* - S_{PAH, cmc}^*}{C_{surf} - CMC} \tag{3}$$

where $S_{PAH, cmc}^*$ is the apparent solubility of PAH compound in g/L at the CMC in g/L; $S_{PAH, mic}^*$ is the total apparent solubility of PAH compound in grams per liter in micellar solution at a particular surfactant concentration greater than the CMC; and C_{surf} is the surfactant concentration at which $S_{PAH, mic}$ is evaluated. SR can be obtained from the slope of solubilization curves above CMC. K_{mc} may be calculated from experimental measurements by using the following formula:

$$K_{mc} = \frac{X_{mc}}{X_a} \tag{4}$$

where X_{mc} is the mass fraction of the PAH compound in the micellar pseudo phase and X_a the mass fraction of the compound in the aqueous phase. The relationship between SR and K_{mc} is given as:

$$K_{mc} = \frac{SR}{(1 + SR)S^*/\rho_w} \tag{5}$$

where ρ_w is the density of water.

Table 2
Mass solubilization ratios and partitioning coefficients of phenanthrene in solubilization tests

SAA	Soil-free			1:20 soil:water		1:10 soil:water	
	SR	R^2	log K_{em} or log K_{mc}	SR*	R^2	SR*	R^2
SCOS	0.0314	0.9983	4.44	0.0454	0.9984	0.0423	0.9977
TW80	0.0224	0.9993	4.27	0.0307	1.000	0.0303	0.9990
TX100	0.0274	0.9995	4.35	0.0316	0.9994	0.0317	0.9998
Brij35	0.0184	0.9976	4.18	0.0184	0.9994	0.0183	0.9991
SDBS	0.0071	0.9902	3.78	0.0077	0.9965	0.0079	0.9879
SDS	0.0169	0.9915	4.15	0.0181	0.9987	0.0219	0.9991

The calculated K_{em} and K_{mc} values and comparison of solubilization ratio (SR) (on the water-free basis) for phenanthrene are shown in Table 2. The results on phenanthrene solubilization by the conventional surfactants such as TX100 are very similar to the previous data [5] if the values of SR are converted into those of molar solubilization ratio (MSR) in Table 2. The difference among the values of partitioning coefficients is characteristic of equilibrium partitioning of solute between pseudo phase and water phase. log K_{em} is slightly larger than log K_{mc}. The contention that the emulsified SCOS system approximates a bulk organic phase is further supported by the similarity of K_{em} values to the octanol-water partition coefficient of phenanthrene. Compared with octanol-water partition coefficient of phenanthrene (log $K_{ow} = 4.45$, ref. [24]), log K_{em} is equivalent to log K_{ow}, while log K_{mc} for phenanthrene is less than log K_{ow} which shows that SCOS microemulsions possess the optimum microscopic organic environment to solubilize non-polar organic compound among the tested SAAs. It is important to point out that the conventional surfactants exist in monomer below its CMC. The partitioning coefficients of organic compounds between the monomer and water are about 1.5–3.0 orders of magnitude less than K_{mc} [4]. Thus, the SCOS solution at low concentration exhibits enormously greater power to enhance the solute solubility than monomeric surfactant.

The values of SR indicate that SCOS is more capable of solubilizing phenanthrene in soil-free system, as shown in Table 2. In the soil–water systems, the effective concentrations of SAA in water are not always equal to the total concentration. It is confirmed that the inorganic ions and organic matter dissolved into water and the sorption of SAA onto soil would affect the solubilization capacity of hydrophobic compounds. However, at high concentration, a satisfactory linearity between the apparent phenanthrene solubility in water and the total surfactant concentration was observed. Table 2 shows the apparent solubilization ratios (SR*) of phenanthrene by SCOS microemulsion and surfactant micelle solutions at the concentration greater than 1000 mg/L in the soil–water system. The values of SR* by SCOS is 1.44, 1.48, 2.47, 5.90, and 2.51 times as that by TX100, TW80, Brij35, SDBS and SDS, respectively, in the 1:10 of soil–water system. Several factors can influence the efficiency of contaminated soils washing with surfactant [6,7]. However, the first one is that the surfactants are efficient in removing the con-

taminant. The greater the apparent solubilizaion extent for a given systems, the fewer pore volumes of surfactant solution needed which reduces capital expenditure and operation cost (equipment and manpower hours). By the data above, the relative solubility enhancement effects by SCOS can now be placed in perspective.

3.3. Extraction of phenanthrene

Extraction studies were used to evaluate the efficiency of SCOS microemulsion to desorb phenanthrene from soil. The conventional surfactant solutions were also employed in the extraction studies to compare the performance. For each SAA system, phenanthrene concentration in water was quantified as a function of mixing time. Fig. 3 shows the plots between the phenanthrene concentration in water and the washing time by 500 mg/L of SAA, respectively. A characterization of desorption rates is through the fitting of measured concentration-time data using rate models. A first-order was employed in to describe the organic compound desorption:

$$\frac{dC}{dt} = k(C_{s,m} - C) \qquad (6)$$

where C (mg/L) is the solute concentration in the aqueous phase at time t; $C_{s,m}$ (mg/L) is the equilibrium saturation (solubility limit) of the solute in water phase, and k (min^{-1}) is the rate constant. The first-order can be used to represent
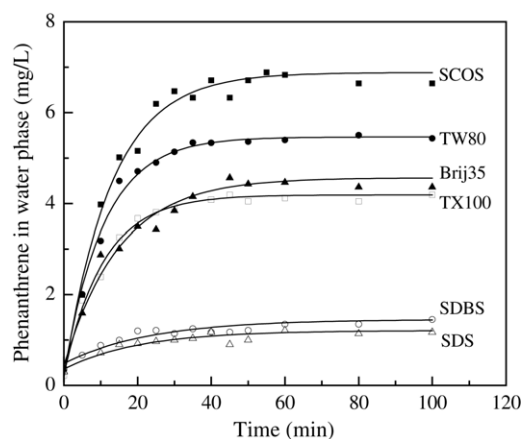

Fig. 3. Plots of the phenanthrene concentrations in water vs. the mixing time (500 mg/L of SAA; 1:10 ratio of soil to water; dots are experimental data and lines are the formulated results).

Table 3
Results of extraction test formulated by the first-order model

SAA	k (min^{-1})	$C_{s,m}$ (mg/L)	R^2	E_{max} (%)
SCOS	0.0783	6.883	0.9864	69.9
TW80	0.0925	5.465	0.9932	55.5
TX100	0.0911	4.185	0.9923	42.5
Brij35	0.0665	4.566	0.9754	46.4
SDBS	0.0429	1.453	0.9038	14.7
SDS	0.0484	1.211	0.8669	12.3

processes such as diffusion and has the same mathematical form as a linear driving force mass transfer model. The integrated form of Eq. (5) is given by:

$$C = C_{s,m}[1 - \exp(-kt)] \tag{7}$$

Eq. (6) was used to estimate mass transfer coefficients for the extraction. It is obvious in Fig. 3 that 500 mg/L of SCOS microemulsion resulted in a high apparent phenanthrene solubility and a largest equilibrium saturation which indicated a high recovery of phenanthrene from soil. The curves grow sharply during the first 20 min, then slowly increase and reach equilibrium up to 60 min as for SCOS and non-ionic surfactant solution. During the growth phase, the sharper the curve, the faster the desorption of phenanthrene, i.e., the larger values of dC/dt in the Eq. (5). No sharp growth of phenanthrene concentration by SDBS and SDS were observed, respectively, due to their existence as monomers in water. Fig. 3 illustrates that SCOS microemulsion led to high and fast extraction for phenanthrene relative to other surfactant solution, given the same dosage of SAAs.

The values of rate coefficients k, the saturation limit $C_{s,m}$, and square regression coefficients R^2 were formulated by Eq. (6) and the maximum of extraction efficiency E_{max} were calculated, as listed in Table 3. The mass transfer coefficient by SCOS microemusion was slightly smaller than those by TX100 and TW80 but larger than those by Brij35, SDBS and SDS, respectively. However, SCOS microemulsion exhibited the largest and fastest extraction for phenanthrene which may be attributed to its high solubilization capacity relative to other surfactant. Surfactant-enhanced soil washing can result from two distinct mechanisms. One occurs below the CMC (soil rollup mechanism) and the other occurs above the CMC (solubilization) [25,26]. Surfactant monomers are responsible for the soil rollup mechanism. In the first step, surfactant monomers accumulate at the soil-contaminant and soil–water interfaces and increase the contact angle between the soil and the contaminant (i.e., change the wettability of the system). Surfactant molecules adsorbed on the surface of the contaminant cause repulsion between the head group of the surfactant molecule and the soil particles, thereby, promoting the separation of contaminant from soil particles. In the second step, convective currents create agitation and abrasion which provides the energy necessary to create additional surface area of oil phase and, thus, displace the oil from the soil rollup mechanism to be significant [16]. The second mechanism for enhanced soil washing is sol-
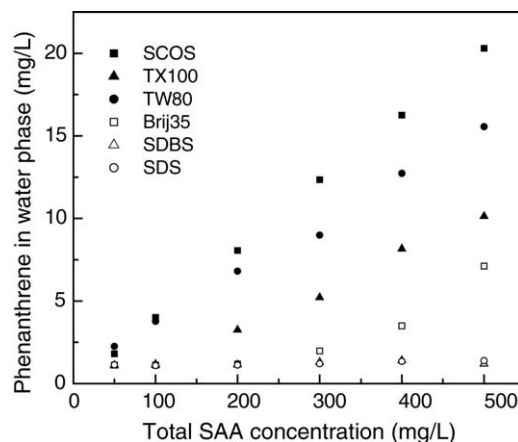

Fig. 4. Solubilization of phenanthrene by SAAs at low concentrations (≤500 mg/L) in 1:10 soil:water systems.

ubilization. Surfactant-enhanced solubilization results from contaminant partitioning into the hydrophobic core of surfactant micelles. Thus, concentration well above the CMC is necessary for this enhancement to be significant. This mechanism has been widely studied in surfactant-enhanced soil washing. Yeom et al. found that the release of PAHs from the MGP soil exhibited a non-equilibrium behavior. Surfactants significantly enhanced the rate of PAH solubilization, the amount solubilized being related to the solubilization capacity of the surfactant. For example, 5500 mg/L of Brij30 desorbed phenanthrene more than POE (10) lauryl ether in the same concentration. The efficiency of phenanthrene desorption by 6000 mg/L of Brij35, TX100 and TW80 followed the order TW80 > TX100 > Brij35 which was consistent with the order of solubilization capacity for phenanthrene. As mentioned above, SCOS system approximates a bulk organic phase. So the rollup mechanism could not be attributed for SCOS washing. Fig. 4 shows the apparent solubilities of phenanthrene by the SAAs below 500 mg/L concentration in the 1:10 soil–water systems. The apparent solubilization capacity followed the order SCOS > TW80 > TX100 > Brij35 » SDBS ∼ SDS. These factors could facilitate the phenanthrene molecules diffuse and increase the desorption rate by SCOS microemulsion.

4. Conclusions

A stable microemulsion was formed when SCOS was mixed in water. No break point was observed in the curves of surface tension-log SCOS concentration and solubilization. SCOS exhibited the largest mass solubilization capacity among the used SAAs in both soil-free system and soil–water system. The partitioning coefficients of phenanthrene between the emulsified phase and the aqueous phase, K_{em}, was larger than those between the micellar pseudo phase and the aqueous phase, K_{mc}. A more efficacious desorption of phenanthrene from spiked soil by SCOS microemulsion

was observed perhaps due to its high solubilization capacity. A rough investigation indicated that the commercial SCOS costs nearly half than the commercial TW 80. The castor oil is not toxic and one of oxytocin in induction of labour. SCOS is a ramification of the reproducible castor oil and aptitude for biodegradation. The results show SCOS would be a potential agent in ex situ washing for PAH-contaminated soils.

Acknowledgements

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