Chemical Engineering Journal 388 (2020) 124191

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Selective removal of phenanthrene from SDBS or TX100 solution by sorption of resin SP850

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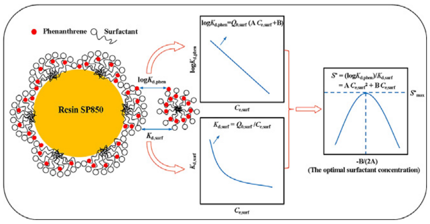
HIGHLIGHTS

- Selective removal technology is developed to recycle soil washing effluent.
- Resin SP850 is an efficient sorbent for selective removal.
- Modified selectivity parameter suggested for surfactant concentration selection in SER.
- Competition and partition controlling phenanthrene removal by SP850.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Selective sorption
Surfactant enhanced remediation
Surfactants
Resin
Phenanthrene

ABSTRACT

Surfactant enhanced remediation (SER) is a promising technology for the removal of hydrophobic organic compounds (HOCs) from contaminated soils. Recycling of soil washing effluent by selective removing of HOCs from surfactant solutions, using techniques such as sorption, is a keyway to reduce the operation costs of SER. In this study, a potential and economical method to recycle washing effluent and lower operation costs of SER, i.e., selective sorption of phenanthrene from an anionic surfactant (sodium dodecylbenzene sulfonate, SDBS) or a nonionic surfactant (Triton X-100, TX100) solution by a resin, SP850, was developed. A modified selectivity parameter (S^*), having a parabolic equation with a maximum S^* value, was developed to evaluate the efficiency of the selective sorption process, the optimal surfactant concentration and SP850 dose for SER. For example, at the given SP850 dose of 1.0 g/L, the optimal concentrations of SDBS and TX100 for SER are about 15000 mg/L and 8000 mg/L, respectively. Moreover, the optimal added SP850 dose for recycling washing effluents is 1.5 g/L, which is independent of surfactant concentration. At the relatively high concentrations of surfactant used in SER, the selective sorption is depended on the sorption of phenanthrene by SP850 and the solubility enhancement of phenanthrene into surfactant micelles in solutions. The observed recycling soil washing effluent method by selective sorption using resins (e.g., SP850) as the adsorbents would be helpful for the application of SER in remediating contaminated soils.

1. Introduction

Surfactant enhanced remediation (SER) is an effective technology for the removal of hydrophobic organic compounds (HOCs) such as phenanthrene from contaminated soils and groundwater [1–5]. However, the loss of surfactants in soil washing process and the treatment of washing effluents, separated from soil using techniques such as centrifugation after soil washing, containing surfactants and HOCs,

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https://doi.org/10.1016/j.cej.2020.124191
Received 1 December 2019; Received in revised form 17 January 2020; Accepted 21 January 2020

increase largely the costs of SER and thus limit its application in the remediation engineers [6,7].

Selectively separating and removal of HOCs from washing effluents but remaining surfactant in solutions is a possible way to recycle washing effluents and lower the operation costs of SER [8]. In the past decades, several techniques including ultrafiltration [9], solvent extraction [10], photochemical treatment [11], electrochemical treatment [12] and biological treatment [5] have been developed to recover surfactant solutions. Sorbents such as activated carbon [13–16], organo layered double hydroxides (organo-LDH) [17] and organo-bentonite [6] were suggested to selectively remove HOCs from surfactant solutions and recycle washing effluents. For example, 1.0 g/L organo-bentonite can remove 63.3% phenanthrene from 5000 mg/L TX100 solution and remain 86.6% TX100 in solution [6]. Moreover, selectivity parameter (*S*), calculated by the ratio of distribution coefficients of phenanthrene to that of surfactant between sorbents and water, was developed to evaluate the efficiency of the selective sorption process [6,13]. Higher selectivity indicates more feasibility and better efficiency for HOCs removing from surfactant solutions and recycling surfactant by selective sorption. However, *S* values of phenanthrene from surfactant solutions by adsorbents decreased continuously with increasing surfactant concentrations [6], and thus failed to obtain an optimal surfactant concentration using *S* value for the application of SER. Therefore, a novel selectivity parameter that can help to find an optimal surfactant concentration for SER should be developed to evaluate the efficiency of the selective sorption process.

Macroporous resins have been widely used as favorable sorbents for the removal of organic contaminants from wastewater due to their large specific surface area and pore volume [18]. For example, resin SP850, specific surface area of 1000 m^2/g, was employed to remove naproxen effectively from wastewater and to purify sulforaphane [19,20]. Moreover, regeneration of resins can easily be achieved by solvent elution using the ethanol or isopropanol solution [21–23]. Therefore, selective sorption of phenanthrene from a nonionic surfactant (Triton X-100, TX100) and an anionic surfactant (sodium dodecylbenzenesulfonate, SDBS), by resin SP850 was investigated at various sorbent dose and surfactant concentrations in this study to check the potential feasibility of resins in SER for recycling surfactant in the soil washing effluents. SDBS and TX100 are typical soil washing reagents with great abilities of enhancing the solubility of HOCs in soil [24–28]. Phenanthrene is a widely observed contaminant in soil and commonly investigated in previous studies regarding SER technology [6,13,16,17,28].

2. Materials and methods

2.1. Chemicals and resin

Phenanthrene (> 98%) was purchased from Fluka Chemistry Co. Anionic surfactant, SDBS ($C_{18}H_{29}NaO_3S$), with purity of 95%, was purchased from Tokyo Chemical Industry. Nonionic surfactant, TX100 ($C_8H_{17}C_6H_4O(OCH_2CH_2)_{9.5}H$), with purity of 98%, was purchased from Sigma Chemical Co. Critical micelle concentration (CMC) of SDBS and TX100 are 963 mg/L and 167 mg/L [28], respectively.

Resin SP850, a macroporous resin, was purchased from Rohm and Haas Company (Philadelphia, PA, USA). The resin was extracted with ethanol for 8 h using the soxlet method to remove the possible impurities, followed by drying in a vacuum oven at 50°C before usage. N_2 adsorption–desorption isotherm of resin SP850 was determined by a physisorption analyzer (Quantachrome, AUTOSORBAS-1) at 77 K. Surface area and total pore volume of SP850, calculated by Brunaer-Emmett-Teller (BET) method, were 953 m^2/g and 1.65 cm^3/g, respectively.

2.2. Sorption experiments

Sorption experiments were conducted at 25 ± 1 °C using a batch equilibration technique with 22 or 40 ml flame sealed glass ampules. A certain amount of SP850 was mixed with 20 or 40 ml of aqueous solutions containing phenanthrene and surfactants. Solid-to-solution ratios were adjusted to achieve that more than 20% of the added phenanthrene was sorbed by SP850. Phenanthrene was first dissolved in methanol as the stock solution and then mixed with the surfactant solution to simulate soil washing effluent containing phenanthrene from 0.1 mg/L to 100 mg/L. The volume ratio of methanol to water in solution was controlled below 2% to avoid cosolvent effects. The mixtures in glass ampules were shaken at 150 rpm for 2 h to reach sorption equilibrium, then SP850 were separated from solutions by standing for 20 min. Equilibrium concentrations of surfactants and phenanthrene in the aqueous phase were determined by a reverse phase HPLC (Shimadzu, LC-20A series, XDB-C18, φ4.6 × 150 mm) with a UV-spectrophotometer at a flow rate of 1 ml/min using mobile phase of 90% methanol and 10% water. The UV wavelengths of 224 and 250 nm were used for surfactant and phenanthrene analysis [6,28], respectively. Experimental uncertainties were evaluated without resin which is < 4% of the initial phenanthrene and surfactant concentrations. Therefore, the sorbed amounts of phenanthrene and surfactants by SP850 were calculated directly by the mass difference of their concentrations in initial and equilibrium solutions.

2.3. Isotherm fitting and data analysis

Freundlich model (Eq. (1)) was a commonly empirical formula used to fit the nonlinear isotherms of organic compounds by adsorbents in the presence of surfactants very well [17,29,30]. Isotherms of phenanthrene from SDBS and TX100 solutions by SP850 were fitted by Freundlich model.

$$q_e = K_f C_e^{1/n} \tag{1}$$

where q_e (mg/g) is the equilibrium adsorbed concentration; C_e (mg/L) is the equilibrium aqueous concentration; K_f [$(mg/g)/(mg/L)^{1/n}$] is Freundlich affinity coefficient, and 1/n is the Freundlich exponential coefficient.

3. Results and discussion

Removal percentages of phenanthrene from SDBS or TX100 solution and the sorptive loss of surfactants by SP850 both increased as SP850 dose increased (Fig. 1). However, the removal percentages of phenanthrene from surfactant solutions and the percent loss of surfactants by sorption both decreased with the increase of initial concentrations of SDBS ($C_{0,SDBS}$) and TX100 ($C_{0,TX100}$) (Fig. 2). The percent removal of phenanthrene from solution by SP850 is much larger than that of surfactants (Figs. 1 and 2). For example, at the SP850 dose of 1.0 g/L, more than 98% and 80% of phenanthrene from 5000 mg/L SDBS and 5000 mg/L TX100 solutions, respectively, were removed, while the percent loss of SDBS and TX100 were both less than 20% (Fig. 1). Compared with activated carbon [13] and organo-bentonite [6], at 5000 mg/L TX100 and adsorbent dose of 1.0 g/L, the removal percentage of phenanthrene from TX100 solution by SP850 is 82.8%, higher than that by activated carbon (65.9%) and organo-bentonite (63.3%). Moreover, resins can be regenerated easily by solvent elution using the ethanol or isopropanol solution [21–23]. Therefore, resin SP850 could be a potential sorbent for the selective separation of phenanthrene from surfactant solutions effectively and recycling surfactants.

Selectivity parameter (*S*) in equation (2) was developed to evaluate the feasibility and efficiency of the selective sorption process for phenanthrene removal and surfactant recovering [13].

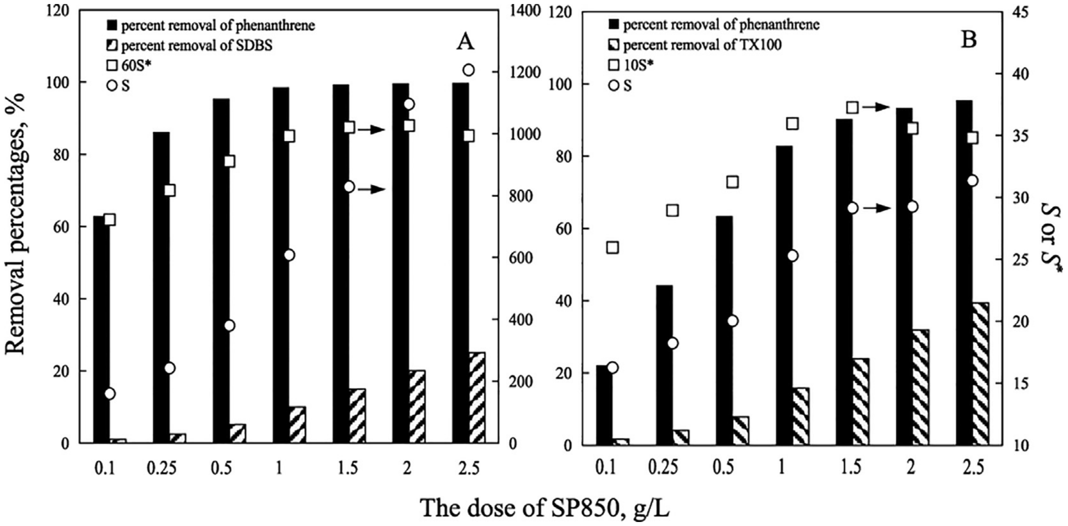

Fig. 1. Sorption removal of phenanthrene (20 mg/L) from 5000 mg/L SDBS (A) or 5000 mg/L TX100 (B) solution by SP850 at various dose. Selectivity values calculated by Equation (3) (S) or Equation (4) (S^*) for phenanthrene removal from SDBS (A) and TX100 (B) solutions by SP850.

$$S = \frac{K_{d,phen}}{K_{d,surf}} = \frac{Q_{phen}}{C_{e,phen}} \times \frac{C_{e,surf}}{Q_{surf}} \tag{2}$$

where $K_{d,phen}$ and $K_{d,surf}$ (L/g) are the distribution coefficients of phenanthrene and surfactant, respectively; Q_{phen} and Q_{surf} (mg/g) are the sorption amount of phenanthrene and surfactant by sorbents, respectively; $C_{e,phen}$ and $C_{e,surf}$ (mg/L) are the equilibrium concentration of phenanthrene and surfactant, respectively. S can also be expressed as the followed form [6]

$$S = \frac{R_{phen}}{1 - R_{phen}} \times \frac{1 - R_{surf}}{R_{surf}} \tag{3}$$

where R_{phen} (%) is the removal percentages of phenanthrene from surfactant solutions; R_{surf} (%) is the percent loss of surfactant. S values of phenanthrene from SDBS and TX100 solutions by SP850, calculated by equation (3), increased as resin dose increased, but decreased with increasing $C_{0,SDBS}$ and $C_{0,TX100}$ (Figs. 1 and 2). Decreasing of phenanthrene S values with increasing $C_{0,TX100}$ was also observed for organobentonite (Fig. 3A) [6]. With the increasing of added SP850 dose, not only S values but also removal percentages of phenanthrene and surfactants were both increased (Fig. 1). Thus, it is difficult to obtain an optimal SP850 dose using S value, i.e., at which the removal percentage of phenanthrene is expected high but percent loss of surfactant is low. Similarly, with the increasing of $C_{0,SDBS}$ and $C_{0,TX100}$, not only S values but also removal percentages of phenanthrene and surfactants were both decreased (Fig. 2). It is also failed to find an optimal surfactant concentration using S value for the application of SER in remediating contaminated soil. Fortunately, by replacing $K_{d,phen}$ in Eq. (2) with $\log K_{d,phen}$, we find a modified selectivity parameter (S^*) (Eq. (4)), which is increased firstly with not only increasing SP850 dose but also $C_{0,SDBS}$ or $C_{0,TX100}$, and then decreased (Figs. 1 and 2). By treatment of $K_{d,phen}$ replaced with $\log K_{d,phen}$ in equation (2), the role of $K_{d,surf}$ in S^* is much important than that in S. Therefore, there is a maximum S^* value, which could be employed to select the optimal surfactant concentration and SP850 dose for SER. For example, at the given SP850 dose of 1.0 g/L, the maximum S^* for phenanthrene was observed at about 15000 mg/L SDBS or 8000 mg/L TX100 solution, respectively (Fig. 2), i.e., 15000 mg/L SDBS and 8000 mg/L TX100 are the optimal concentrations for SER. In this case, more than 90% and 75% of phenanthrene from 15000 mg/L SDBS and 8000 mg/L TX100 solutions could be removed by SP850, while the percent loss of SDBS and TX100 were < 5% and 10%, respectively (Fig. 2). Moreover, using the

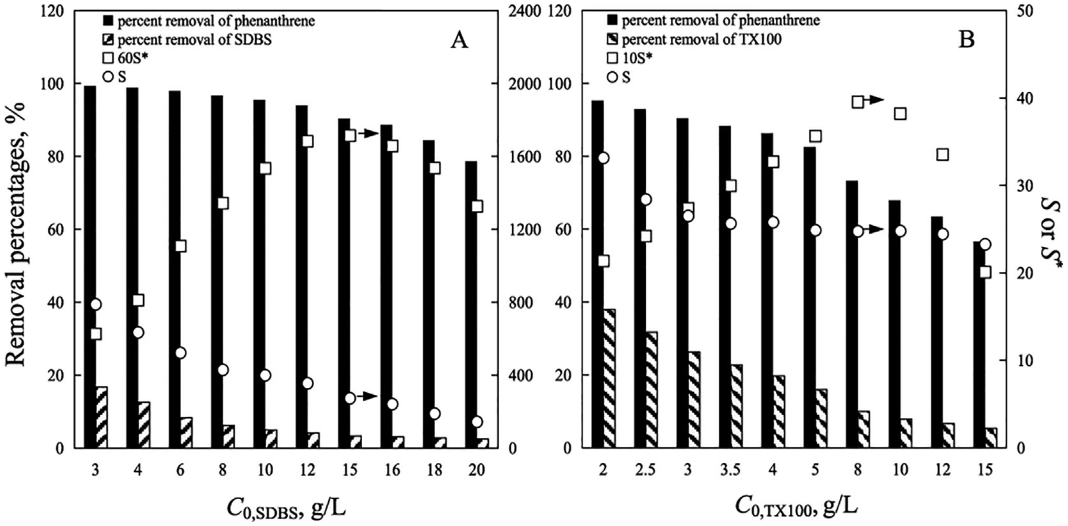

Fig. 2. Sorption removal of phenanthrene (20 mg/L) from SDBS (A) and TX100 (B) solutions by SP850 at 1 g/L. Selectivity values calculated by Equation (3) (S) or Equation (4) (S^*) for phenanthrene removal from SDBS (A) and TX100 (B) solutions by SP850.

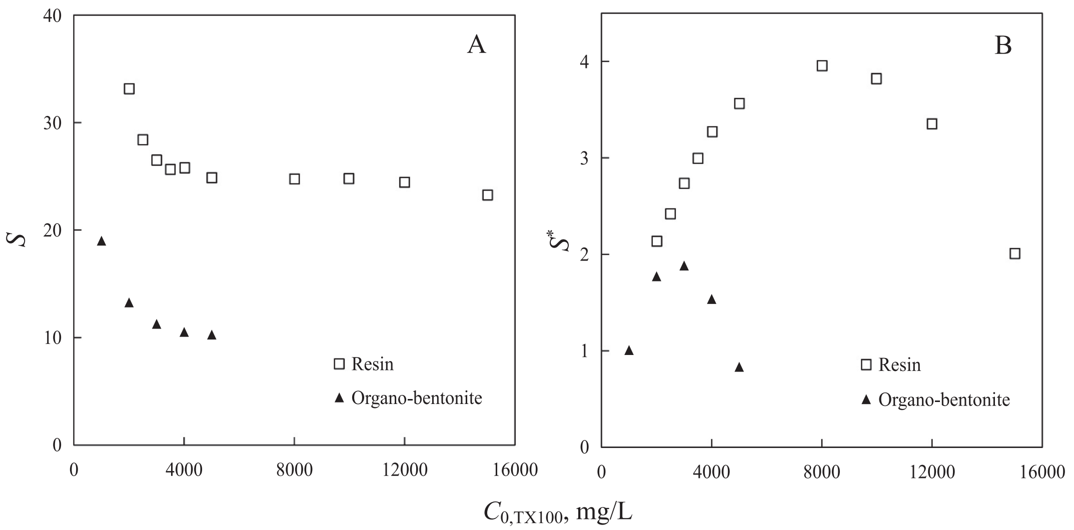

Fig. 3. Selectivity values calculated by Equation (3) (A) and Equation (4) (B) for phenanthrene (20 mg/L) removal from TX100 solution by sorbents at 1 g/L including resin SP850 in this study and organo-bentonite [6].

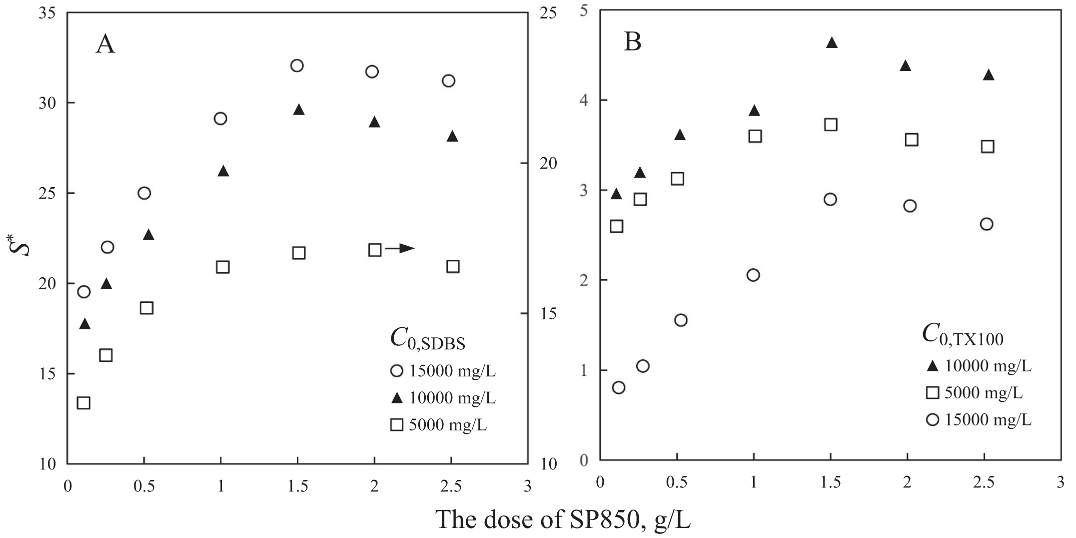

Fig. 4. Selectivity values (S^*) for phenanthrene (20 mg/L) removal by SP850 at given initial concentrations of SDBS ($C_{0,SDBS}$) in plot A and at that of TX100 ($C_{0,TX100}$) in plot B.

maximum S^* value, one can obtain the optimal added dose of SP850, i.e., 1.5 g/L (Fig. 4), too. This optimal SP850 dose is independent of surfactant concentration (Fig. 4). In addition, by S^* calculation, the maximum S^* value for phenanthrene by organo-bentonite from the TX100 solution was also observed, which can be used to select the optimal TX100 concentration for the application of SER (Fig. 3B).

$$S^* = \frac{\log K_{d,phen}}{K_{d,surf}} \tag{4}$$

The increase and the followed decrease of S^* values with increasing $C_{0,SDBS}$ or $C_{0,TX100}$ (Fig. 2) should be attributed to the effects of the distribution of SDBS or TX100 between SP850 and water on the sorption of phenanthrene by SP850 [31–34]. Surfactant including SDBS and TX100 exists as monomers at $C_{e,surf}$ < CMC and micelles at $C_{e,surf}$ > CMC in water (Fig. 5) [28,31]. However, on solid adsorbents such as SP850, it exists not only monomers and micelles but also hemi-micelles (Fig. 5) [31,32]. At relatively low concentrations, SDBS or TX100 adsorbed on SP850 as monomers. With the increase of SDBS/TX100 concentrations, more surfactant adsorbed to form hemi-micelles and then micelles until a plateau value (535 mg/g for SDBS and 788 mg/g for TX100) is reached at about $C_{e,surf}$ = 2CMC (Figs. 5 and 6). At $C_{e,surf}$ < CMC, competition of phenanthrene by surfactant monomers and hemi-micelles will significantly decrease the sorption of phenanthrene on SP850 surface (Fig. 6) [31], while the sorption decrease of phenanthrene by solubility enhancement of phenanthrene in surfactant solution [3,28,31,35–37] and sorption increase by partitioning of phenanthrene into the adsorbed surfactant monomers and hemi-micelles [31,32] are insignificant (Fig. 6). At CMC < $C_{e,surf}$ < 2CMC, the competition of phenanthrene by adsorbed micelles will also significantly decrease phenanthrene sorption on SP850, accompanying the insignificant sorption decrease of phenanthrene by solubility enhancement due to the few micelles formed in water and the insignificant sorption increase of phenanthrene by partitioning into the adsorbed micelles (Fig. 6). Therefore, a negative relationship of logarithm sorption coefficient (logK_f) of phenanthrene by SP850 with $C_{e,SDBS}$ or $C_{e,TX100}$ (Fig. 6) below 2CMC was observed, which should largely be attributed to the competition of adsorbed surfactant for phenanthrene on SP850. logK_f values in Fig. 6 were obtained from Freundlich model fitted isotherms of phenanthrene by SP850 at various SDBS and TX100 concentrations. Freundlich model can fit isotherms of phenanthrene by SP850 in the presence of SDBS and TX100 very well,

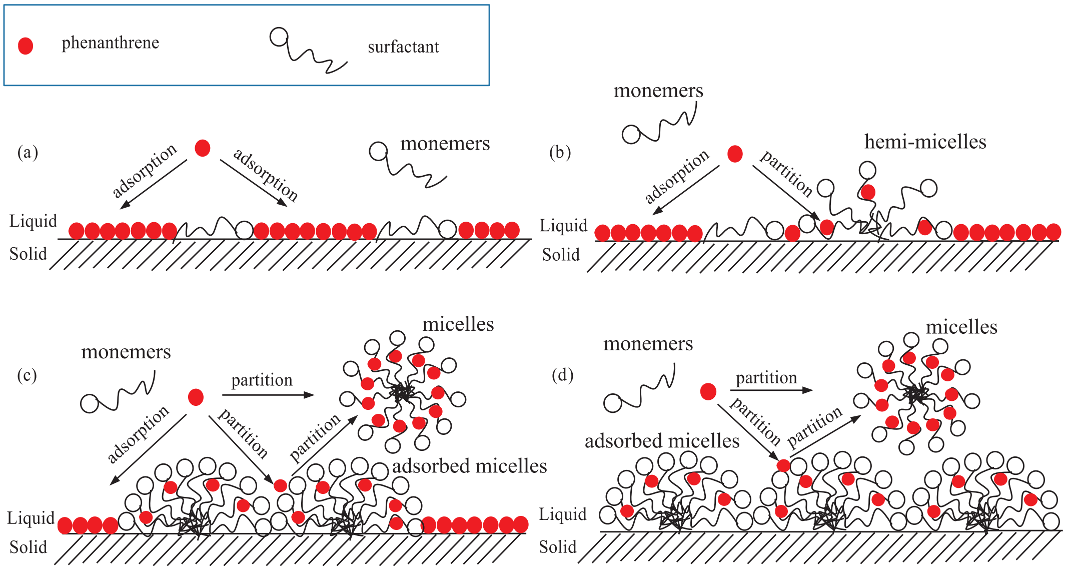

Fig. 5. Scheme of phenanthrene sorption from surfactant solution by resin SP850.

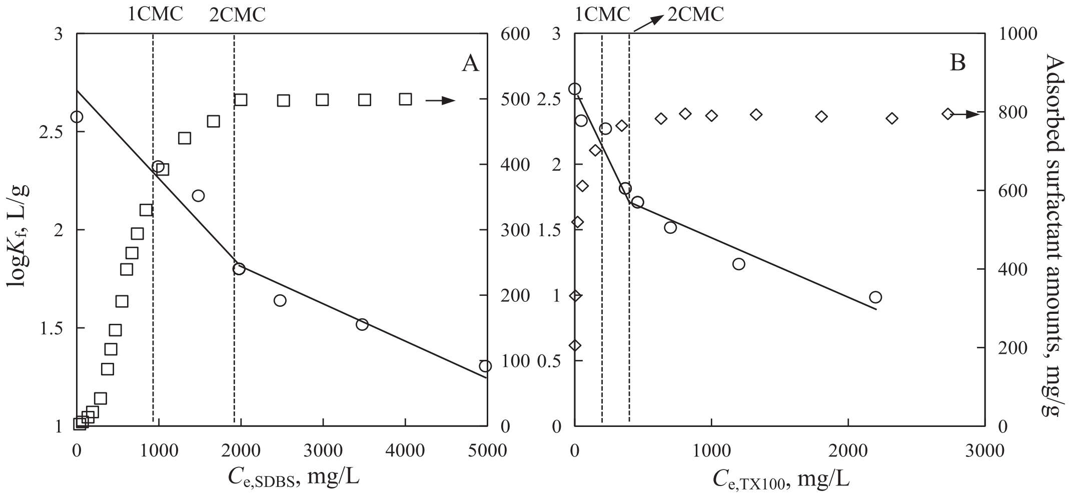

Fig. 6. Correlations of Freundlich affinity coefficient (K_f) with SDBS equilibrium concentrations ($C_{e,SDBS}$) in plot A and TX100 equilibrium concentrations ($C_{e,TX100}$) in plot B. Sorptive curves of SDBS (A) and TX100 (B) by SP850.

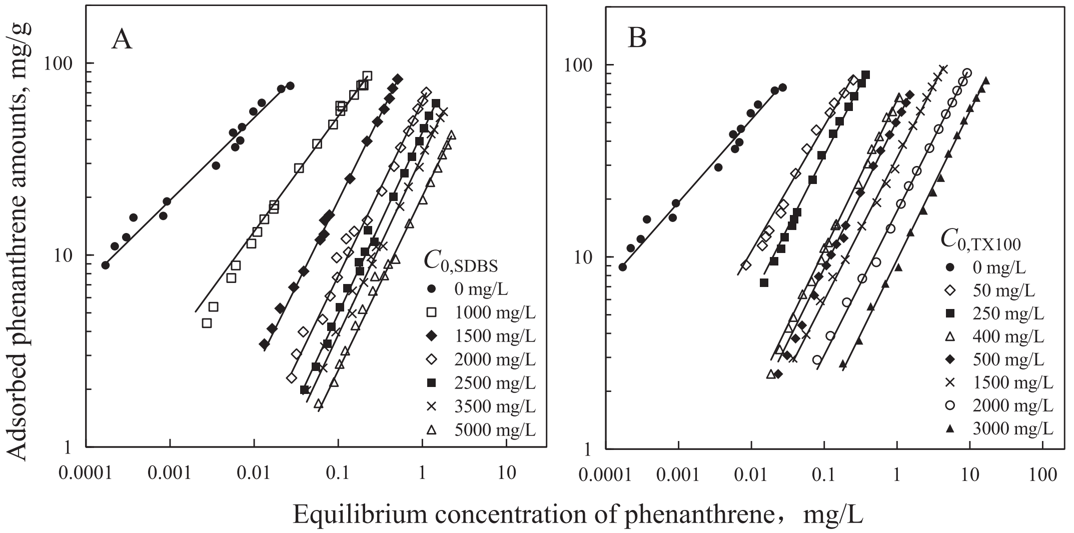

Fig. 7. Isotherms of phenanthrene by SP850 at given initial concentrations of SDBS ($C_{0,SDBS}$) in plot A and at that of TX100 ($C_{0,TX00}$) in plot B. Solid lines are the isotherms fitted by Freundlich model.

Table 1
Freundlich model fitted isotherm parameters of phenanthrene by SP850 in the presence of SDBS and TX100.

Surfactant	Initial concentrations (mg/L)	K_f	1/n	F	P	R^2	N
SDBS	0	376 ± 40	0.429 ± 0.023	1160	< 0.001	0.978	15
	1000	210 ± 6	0.600 ± 0.015	6084	< 0.001	0.996	21
	1500	149 ± 2	0.890 ± 0.012	15,731	< 0.001	0.999	16
	2000	63.2 ± 0.6	0.910 ± 0.019	6479	< 0.001	0.997	19
	2500	43.6 ± 0.4	0.944 ± 0.018	7108	< 0.001	0.997	18
	3500	32.9 ± 0.3	0.933 ± 0.016	9396	< 0.001	0.998	19
	5000	20.2 ± 0.2	0.906 ± 0.018	7109	< 0.001	0.997	18
TX100	0	376 ± 40	0.429 ± 0.023	1160	< 0.001	0.978	15
	50	215 ± 11	0.652 ± 0.025	1516	< 0.001	0.988	15
	250	188 ± 4	0.747 ± 0.013	8162	< 0.001	0.998	15
	400	65.4 ± 0.6	0.780 ± 0.013	8291	< 0.001	0.998	18
	500	51.3 ± 0.2	0.769 ± 0.008	23,033	< 0.001	0.999	19
	1500	32.8 ± 0.5	0.743 ± 0.014	8891	< 0.001	0.998	16
	2000	17.3 ± 0.2	0.749 ± 0.007	36,458	< 0.001	0.999	16
	3000	9.65 ± 0.36	0.773 ± 0.016	7507	< 0.001	0.997	16

[a] All estimated parameter values and standard errors were determined by a commercial software (SPSS 20.0) with nonlinear regression; N is the number of experimental data.

as is indicated by good correlation coefficients values (R^2 close to 1) and the significance of F test ($P < 0.001$) (Fig. 7, Table 1). At $C_{\mathrm{e,surf}} >$ 2CMC, sorption of surfactant by SP850 reached a plateau value (i.e., 535 mg/g for SDBS and 788 mg/g for TX100) (Fig. 6). No more phenanthrene can be competitived by the adsorbed surfactant and be partitioned into the adsorbed micelles. However, more surfactant micelles formed in water which can decrease the phenanthrene sorption by solubility enhancement [35–37] (Figs. 5 and 6). Thus, another negative relationship of $\log K_f$ by SP850 with $C_{\mathrm{e,SDBS}}$ or $C_{\mathrm{e,TX100}}$ (Fig. 6) above 2CMC was observed because of the solubility enhancement of phenanthrene into surfactant micelles in solution. The removal percentages of phenanthrene from TX100 solution was lower than that from SDBS solution at a given surfactant concentration and a given SP850 dose (Fig. 1), which should be attributed to the higher molar solubilization ratio of phenanthrene in TX100 solution (0.119) than that in SDBS solution (0.0182) [28]. For example, at surfactant concentration of 5000 mg/L and SP850 dose of 1.0 g/L, the removal efficiency of phenanthrene by SP850 from TX100 solution was 82.8%, significantly lower than that from SDBS solution (98.6%).

For soil washing, the used surfactant concentrations in SER should be high enough to form large quantitative micelles for solubility enhancement of HOCs, i.e., the equilibrium concentrations of surfactant in washing effluents are much higher than 2CMC [3,32,38]. In this case, only solubility enhancement of phenanthrene into surfactant micelles in solutions can decrease the sorption of phenanthrene on SP850 surface. Therefore, there is a negative linear relationship of the logarithm distribution coefficients ($\log K_{\mathrm{d,phen}}$) of phenanthrene with $C_{\mathrm{e,SDBS}}$ or $C_{\mathrm{e,TX100}}$ (Fig. 8, equations 5 and 6), due to the observed negative relationship of $\log K_f$ by SP850 with $C_{\mathrm{e,SDBS}}$ or $C_{\mathrm{e,TX100}}$ above 2CMC in Fig. 6. Moreover, at $C_{\mathrm{e,surf}} >$ 2CMC, the distribution coefficients of SDBS ($K_{\mathrm{d,SDBS}}$) or TX100 ($K_{\mathrm{d,TX100}}$) between SP850 and water decreased with $C_{\mathrm{e,SDBS}}$ or $C_{\mathrm{e,TX100}}$ to give a negative relationship (Fig. 8, equations 7 and 8), because the sorption amount of surfactant has reached the plateau value ($Q_{0,\mathrm{surf}}$) on SP850 (Fig. 6). $K_{\mathrm{d,SDBS}}$ or $K_{\mathrm{d,TX100}}$ are the ratio of the adsorbed amount of surfactant (Q_{surf}) to $C_{\mathrm{e,surf}}$. According to equations 5–8, equation (4) can be transformed into a parabolic equation (i.e., $S^* = \mathrm{A}C_{\mathrm{e,surf}}^2 + \mathrm{B}C_{\mathrm{e,surf}}$). A and B are the coefficients of the quadratic and primary terms of the equation, respectively. Therefore, the parabolic equations (equations 9 and 10) were obtained for S^* values of phenanthrene by SP850 in SDBS or TX100 solution. For the parabolic equations, there is a maximum S^* value, which occurs at $C_{\mathrm{e,surf}}$ = -B/(2A), implying that $C_{\mathrm{e,surf}}$ = -B/(2A) could be the optimal surfactant concentration for soil washing. For example, the observed optimal surfactant concentrations of about 15000 mg/L SDBS and 8000 mg/L TX100 (Fig. 2) can be also calculated from the parabolic equations 9 and 10 using $C_{\mathrm{e,surf}} = -\mathrm{B}/(2\mathrm{A})$, respectively.

$$\log K_{\mathrm{d,phen}} = -7.69(\pm 0.01)\times 10^{-5}\, C_{\mathrm{e,SDBS}} + 2.08(\pm 0.02)$$
$$R^2 = 0.998,\ F = 2.93\times 10^{3},\ P < 0.001,\ N = 8 \tag{5}$$

$$\log K_{\mathrm{d,phen}} = -7.05(\pm 0.01)\times 10^{-5}\, C_{\mathrm{e,TX100}} + 1.03(\pm 0.05)$$
$$R^2 = 0.953,\ F = 123,\ P < 0.001,\ N = 8 \tag{6}$$

$$K_{\mathrm{d,SDBS}} = 535(\pm 41)\times C_{\mathrm{e,SDBS}}^{-1.01(\pm 0.01)}$$
$$R^2 = 0.999,\ F = 4.34\times 10^{4},\ P < 0.001,\ N = 8 \tag{7}$$

$$K_{\mathrm{d,TX100}} = 788(\pm 7)\times C_{\mathrm{e,TX100}}^{-1.00(\pm 0.00)}$$
$$R^2 = 0.999,\ F = 2.42\times 10^{6},\ P < 0.001,\ N = 8 \tag{8}$$

$$S^* = -1.50(\pm 0.03)\times 10^{-7}\, C_{\mathrm{e,SDBS}}^2 + 4.09(\pm 0.06)\times 10^{-3}\, C_{\mathrm{e,SDBS}}$$
$$R^2 = 0.980,\ F = 1.03\times 10^{4},\ P < 0.001,\ N = 8 \tag{9}$$

$$S^* = -7.03(\pm 0.61)\times 10^{-8}\, C_{\mathrm{e,TX100}}^2 + 1.11(\pm 0.07)\times 10^{-3}\, C_{\mathrm{e,TX100}}$$
$$R^2 = 0.863,\ F = 205,\ P < 0.001,\ N = 8 \tag{10}$$

4. Conclusions

Resins such as SP850 was investigated and suggested in this study as a potential adsorbent for the selective removal of phenanthrene from soil washing effluents containing SDBS or TX100 and for the recycling of washing effluents to lower operation costs of SER. A modified selectivity parameter (S^*), i.e., the ratio of the logarithm distribution coefficients of phenanthrene ($\log K_{\mathrm{d,phen}}$) to distribution coefficients of surfactant ($K_{\mathrm{d,surf}}$) between SP850 and water, was developed to evaluate the efficiency of the selective sorption process. Moreover, a parabolic equation, i.e., $S^* = \mathrm{A}C_{\mathrm{e,surf}}^2 + \mathrm{B}C_{\mathrm{e,surf}}$, having a maximum S^* value at $C_{\mathrm{e,surf}} = -\mathrm{B}/(2\mathrm{A})$, was established to calculate the optimal surfactant concentration (i.e., $-\mathrm{B}/(2\mathrm{A})$) for soil washing. For example, the observed optimal surfactant concentrations of about 15000 mg/L SDBS and 8000 mg/L TX100 can be also calculated from the parabolic equations using $C_{\mathrm{e,surf}} = -\mathrm{B}/(2\mathrm{A})$, respectively. In addition, the optimal added SP850 dose for recycling soil washing effluents is 1.5 g/L, which is independent of surfactant concentration. At the relatively high concentrations of surfactant used in SER, i.e., the surfactant equilibrium concentrations in washing effluents are commonly higher than 2CMC, the selective sorption is depended on not only the sorption of phenanthrene by SP850 but also the solubility enhancement of phenanthrene into surfactant micelles in solutions. The observed recycling soil washing effluent method by selective sorption using resins (e.g., SP850)

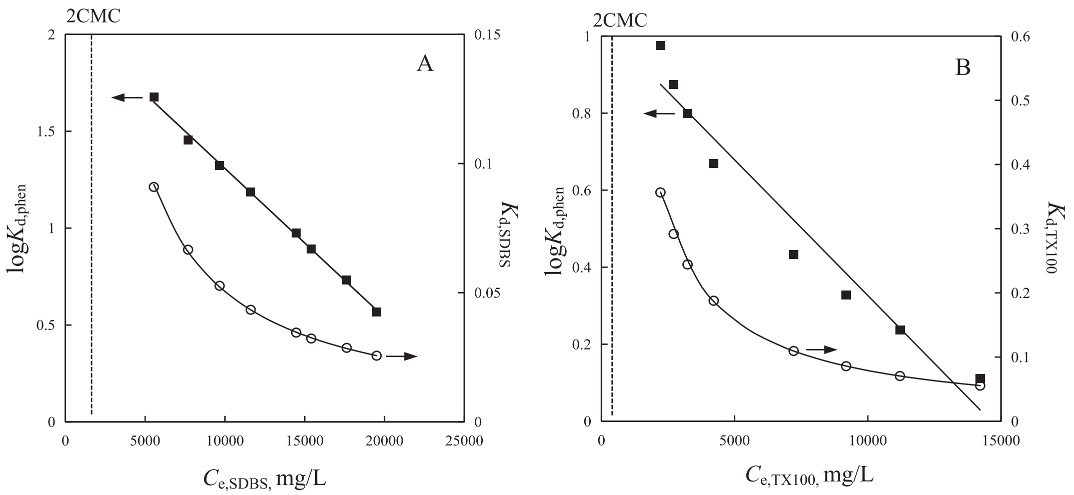

Fig. 8. Correlations of logarithm distribution coefficients of phenanthrene (log $K_{d,phen}$) and distribution coefficients of SDBS ($K_{d,SDBS}$) with SDBS equilibrium concentrations ($C_{e,SDBS}$) in plot A. Correlations of log $K_{d,phen}$ and distribution coefficients of TX100 ($K_{d,TX100}$) with TX100 equilibrium concentrations ($C_{e,TX100}$) in plot B.

as the adsorbents would be helpful for the application of SER in remediating contaminated soils. Furthermore, additional experiments such as the regeneration of resins (e.g., SP850) and selective sorption of HOCs from washing effluents containing mixture surfactants by resins, would be conducted to establish more feasible applications of resins and the modified selectivity parameter.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported partly by the National Key Research and Development Program of China (2017YFA0207001), the National Natural Science Foundation of China (21621005, 21777138), and the Key Research and Development Program of Zhejiang Province, China (2019C03105 and 2015C03022).

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