

Effect of coagulant addition on the sedimentation of a surfactant-containing washing solution used for phenanthrene-contaminated soil

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Abstract—The coagulation of soil particles from a soil-washing solution containing the nonionic surfactant Triton X-100 (TX100) was investigated using various coagulants, such as chitosan (CS), polyacrylamide (PAA), and polyaluminum chloride (PAC). Soil contaminated with phenanthrene (PHE) was washed with aqueous TX100 solutions at concentrations ranging from 0.1 to 20 g/L. The effectiveness of CS (5 mg/L) as a coagulant in the system was compared with PAA (50 mg/L) and PAC (50 mg/L), and the results indicated that the system with CS exhibited a more effective separation of soil than those with PAA and PAC. The removal efficiency of PHE ($R_r=81.7\%$) and the selective separation factor ($SSF=14.2$) at 10 g/L TX100 were the highest for the system with CS (5 mg/L), indicating that the selection of CS as a coagulant in surfactant-mediated soil washing markedly improved both PHE removal and soil separation.

Key words: Chitosan, Coagulation, Phenanthrene, Soil Washing, Surfactant

INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) are the most common types of widespread pollutants in the environment, and their occurrence in contaminated soil and groundwater can have severe and persistent effects on animal and human health as well as environmental quality. PAHs, which are generally hydrophobic organic contaminants consisting of two or more fused benzene rings, often have allergenic, mutagenic, and carcinogenic effects [1]. They are released into the environment as a result of the incomplete combustion of fossil fuels, from old gas-manufacturing plants, or from spills of hydrocarbon fuels [2]. The widespread occurrence of PAHs in subsurface environments has led to intensive studies on the environmental mobility and fate of these contaminants and their remediation [3]. Soil contaminated with PAHs poses remediation difficulties because of their hydrophobic nature and, moreover, PAHs act as long-term contaminant sources by strongly sorbing to soil [4]. Thus, the increase of PAH mobility by enhancing their aqueous solubility is the most important step in the remediation of PAH-contaminated soils.

A promising technology for the rapid removal of PAHs from soil contaminated with these hazardous organic contaminants is soil washing using surfactant solutions [5-7]. Surfactants are amphiphilic molecules containing a hydrophilic head and a hydrophobic tail. Surfactant-mediated soil-washing processes involve the enhancement of the aqueous solubility of PAHs by partitioning them into the hydrophobic cores of surfactant micelles [8,9]. Normally, nonionic surfactants are applied in soil washing for the remediation of soil contaminated with PAHs because of their low cost, low toxicity, and low sorption onto soils [10]. In some cases, anionic surfactants may also be used for soil washing to enhance washing efficiency with

or without nonionic surfactants [11]. However, the operating costs of surfactant-mediated soil-washing processes in practical applications are quite high because the performance of soil washing increases only with increased surfactant dosages [12]. To reduce the operating costs of these processes, various technologies including ultrafiltration, pervaporation, precipitation, foam fractionation, solvent extraction, photochemical treatment, and selective adsorption by activated carbon have been developed for recovering and reusing the surfactants [10,12,13]. The application of these recovery technologies inevitably requires proper separation of soil particles from the used soil-washing solution. It has been reported that the presence of soil particles reduces both surfactant recovery (by 0.4-3.9%) and contaminant removal (by 0-23.1%) during selective adsorption [14]. The soil particles could possibly be removed from the soil-washing surfactant solution by coagulation [15].

Chitosan (CS), a biopolymer of glucosamine and N-acetyl glucosamine, is derived from the alkaline deacetylation of crustacean chitin, which is the second-most abundant biopolymer in nature. The high content of positively charged amine groups in the CS structure endows it with polyelectrolyte properties [16]. The applications of CS in the pharmaceutical and biomedical [17], food processing [18], and environmental fields (e.g., as an adsorbent) [19] have been reported in the literature. CS has found many applications as a coagulant in a wide variety of suspensions [20-25] because of its biodegradability, low toxicity, and environmentally friendly nature [16]. Thus, the application of CS as a coagulant in water-treatment processes facilitates water purification without the production of hazardous sludge as with conventional chemical coagulants [22,26,27]. However, to date, the effects of coagulants in systems containing a surfactant-containing soil-washing solution and soil contaminated with hazardous organic compounds have not been studied. In this work, we studied the distribution of soil particles and phenanthrene (PHE) in a combined system of soil washing with Triton X-100 (TX100) for PHE extraction followed by the coagulation of soil

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Table 1. The physico-chemical properties of soil [28]

Test soil	pH (-)	OM ^a (%)	DOM ^b (mg/kg)	Particle size (mm)	Soil texture [%]		
					Clay	Silt	Sand
BS	8.21	12.8±0.09	103.2±18.0	<0.075	3.2	48.2	48.6

^aOrganic matter content based on mass^bDissolved organic matter in DI water

particles from the soil-washing solution using various coagulants, such as CS, polyaluminum chloride (PAC), and polyacrylamide (PAA).

MATERIALS AND METHODS

1. Materials

The Soil sample (BS) was purchased from Donghae Chemicals (BENT-1, Korea). Table 1 describes the physicochemical properties of soil used in this study and the detailed methods for determining the physicochemical properties of the soil were described in our previous report [28]. CS (>85% deacetylation), PHE (>98%), TX100, and PAA were purchased from Sigma Chemical Co., USA. PAC was purchased from E-Young Chemical Company, Korea. All other analytical-grade chemicals were purchased from Sigma Chemical Co., USA. The chemical and physical properties of PHE and TX100 are summarized in Table 2. PHE (C₁₄H₁₀) is a tricyclic PAH with a molecular weight of 178 g/mol and the solubility of PHE (C_s) in aqueous solution is 1.0×10⁻⁵ (mol/L) [8]. TX100 [octylphenolpoly(ethylene glycol ether)₅] is a nonionic surfactant with a molecular weight of 625 g/mol. The critical micelle concentration (CMC) of TX100 in aqueous solution is 0.106 g/L, and the weight solubilization ratio (WSR) of TX100 for PHE (g PHE/g TX100) is 0.025 [8]. TX100 was used as a model nonionic surfactant in this study because it is known to be one of the surfactants most widely used for soil washing, both in laboratory research and field applications [8].

2. Preparation of Coagulant Solutions and PHE-contaminated Soil

A 5.0 g/L stock solution of CS was prepared by dissolving CS in a 1 v/v% acetic acid solution by gentle magnetic stirring overnight at 150 rpm. The pH of the chitosan solution was then adjusted to 5.0 by adding 0.1 (N) NaOH. The 50 g/L stock solutions of PAA and PAC were prepared in deionized water.

To prepare PHE-contaminated soil, 4 g of PHE was dissolved in

100 mL of dichloromethane (CH₂Cl₂) and then mixed with 1 kg of soil particles in a glass container. To prepare solvent-wet soil, soil particles were manually stirred for 30 min using a glass rod. As-prepared solvent-wet soil was then moderately heated on a hot plate in a hood to completely evaporate the CH₂Cl₂, and the evaporation process was combined with intermittent manual mixing. The resulting PHE-contaminated soil was kept in a closed container fitted with a lid and used for soil washing experiments within a week.

3. Soil Washing and Coagulation

Soil washing using TX100 involved the addition of 0.125 g of PHE-contaminated soil particles (5 g/L) to 25 mL of TX100 solution of the desired concentration in a 50 mL Falcon tube; TX100 concentration was varied in the suspension from 0.1 to 20 g/L. The extraction of PHE from soil using TX100 was performed under shaking (200 rpm) at 30 °C for one day.

After the soil was washed with the surfactant solution, various coagulants (CS, PAC, or PAA) were added to the soil-washing suspension for the coagulation of soil particles from the washing solution. The PAA, PAC, and CS concentrations were fixed at 50, 50, and 5 mg/L, respectively. Five mL of coagulant solution containing a given concentration of CS, PAA, or PAC was added to the washed soil suspension, and then vortexing for 1 min was immediately applied to the coagulating system for proper mixing of all the components followed by gravimetric coagulation under static conditions. Gravimetric coagulation under static conditions was performed to examine the effects of surfactant concentration more accurately without the interference of the additional variable of mixing. After coagulation of the washing solution for 30 min, its absorbance was measured at 540 nm using a DR5000 spectrophotometer (Hach, USA) to determine the amount of suspended soil particles.

To determine the aqueous-phase concentration of PHE after soil washing and coagulation, 1.5 mL of soil-washing solution was centrifuged at 10,000 rpm for 10 min to precipitate suspended soil particles from the washing solution, and the clear supernatant was directly injected into a high-performance liquid chromatography system (HPLC, Dionex, USA). To determine the total PHE in the suspension, 5 mL of soil-washing suspension was extracted with 20 mL of a butanol/acetonitrile (4:1) solvent mixture for 2 h at 200 rpm and 30 °C. The amounts of PHE bound to the soil particles were determined by a mass-balance calculation.

4. Analytical Methods

The PHE concentration was analyzed using HPLC with a UV detector at 250 nm. The analytical column contained Acclaim® 120, C18 5 μm, 120 Å (4.6×150 mm) and the mobile phase was 85% (v/v) acetonitrile and 15% (v/v) deionized water at a flow rate of 1.5 mL/min. All liquid samples were analyzed immediately after sample preparation within 1 h to minimize the adsorption of PHE onto the walls of sample vials. The size distribution of the sus-

Table 2. Chemical properties of phenanthrene and surfactant

Name	Chemical formula	MW (g/mol)	CMC (g/L)	WSR (g/g)	C _s (mol/L)
TX100	C ₁₄ H ₂₂ O(C ₂ H ₄ O) ₅	625	0.106 ^a	0.025 ^a	-
PHE	C ₁₄ H ₁₀	178	-	-	1.0×10 ^{-5a}

MW: molecular weight; CMC: critical micelle concentration of surfactant in aqueous solution; WSR: weight solubilization ratio of surfactant for PHE (g PHE/g surfactant); C_s: aqueous solubility of PHE at 25 °C

^aRef. [8]

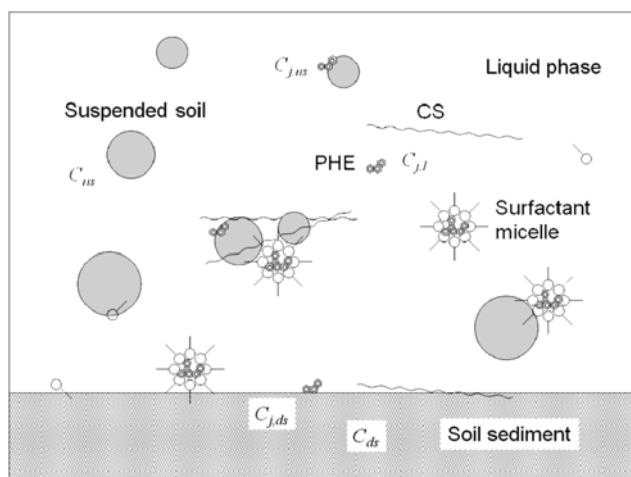


Fig. 1. Schematic of the aqueous surfactant/soil/PHE/CS system and the distribution of soil and PHE during sedimentation.

pended soil particles after sedimentation for 30 min with a soil suspension at a concentration of 5 g/L was analyzed using a Zetasizer Nano-ZS (Malvern, UK).

RESULTS AND DISCUSSION

1. Aqueous Surfactant/Soil/PHE/CS System During Sedimentation

Fig. 1 illustrates the conceptual model for the configuration and distribution of soil and PHE in the aqueous TX100/soil/PHE/CS system during sedimentation using CS as a model coagulant. At a given time during the sedimentation process, soil particles can be separately considered as either coagulated as sediment (ds) or suspended in the liquid phase (us), with their concentrations indicated by C_{ds} and C_{us} , respectively. The total amount of PHE (j) in the system is distributed into three parts: PHE bound to the soil particles in soil sediment ($C_{j,ds}$), PHE bound to suspended soil particles ($C_{j,us}$), and PHE extracted from soil particles into the liquid phase ($C_{j,l}$). The conformations assigned to the $C_{j,ds}$ or $C_{j,us}$ fractions include PHE bound to soil particles, PHE-surfactant complex (micelle or hemimicelle forms) bound to soil particles, and aggregates of fine particles containing PHE and/or surfactants associated with CS fibers. The liquid-phase PHE concentration ($C_{j,l}$) includes solvated PHE in the aqueous solution and PHE entrapped in the micellar form. From the viewpoint of a separation process, soil and PHE are separated into two distinct parts: soil sediment with PHE as the recovered part and the liquid with dissolved PHE and PHE bound to suspended soil as the removed part. The sedimentation of suspended soil particles through the addition of a coagulant, such as CS, would definitely promote better soil removal in the system. However, the effect of coagulant addition on PHE removal may be difficult to predict due to the very complex nature of the effects of the coagulant on PHE solubilization and sorption.

2. Distribution Analysis

The equations for the distribution of soil and PHE were mathematically established and thereby the PHE removal efficiency and selective separation factor were derived. This mathematical expression reflects the effect of coagulants on the separation of PHE and

soil in the surfactant-mediated soil washing process. The system includes three conceptual phases: the sedimented soil phase, the suspended soil phase, and the liquid phase. The soil particles are distributed in the sedimented and suspended phases, and their fractions are expressed as follows:

$$f_{ds}(\%) = \frac{C_{ds}}{C_{ds} + C_{us}} \times 100 \quad (1)$$

$$f_{us}(\%) = \frac{C_{us}}{C_{ds} + C_{us}} \times 100 \quad (2)$$

The parameters $f_{ds}(\%)$ and $f_{us}(\%)$ represent the percentages of soil coagulated after sedimentation using a coagulant and soil particles suspended in the washing solution, respectively. The values of C_{ds} (g/L) and C_{us} (g/L) represent the concentrations of coagulated soil and suspended soil particles in the washing solution, respectively, after sedimentation.

The value of $f_{j,ds}(\%)$ represents the percentage of PHE in the coagulated soil particles after sedimentation and is calculated as follows:

$$f_{j,ds}(\%) = \frac{C_{j,ds} \times C_{ds}}{C_{j,s,ini} \times f_{s/l}} \times 100 \quad (3)$$

where $C_{j,ds}$ (mg/g) represents the concentration of PHE in the coagulated soil particles after sedimentation, $C_{j,s,ini}$ indicates the total initial concentration of PHE in the soil (here, 4,000 mg/kg), and $f_{s/l}$ indicates the soil concentration in the system (here, 0.005 kg/L).

Similarly, $f_{j,us}(\%)$ represents the percentage of PHE in the suspended soil particles after sedimentation and can also be calculated as:

$$f_{j,us}(\%) = \frac{C_{j,us} \times C_{us}}{C_{j,s,ini} \times f_{s/l}} \times 100 \quad (4)$$

Here, $C_{j,us}$ (mg/g) indicates the amount of PHE in the suspended soil particles after sedimentation. The value $f_{j,l}(\%)$ for the percentage of PHE in the liquid phase after sedimentation is determined by the equation:

$$f_{j,l}(\%) = \frac{C_{j,l}}{C_{j,s,ini} \times f_{s/l}} \times 100 \quad (5)$$

The experimentally determined $C_{j,l}$ (mg/L) indicates the amount of PHE in the liquid phase after soil washing using a surfactant followed by the sedimentation of soil particles using a coagulant. The percentages of soil and PHE in each phase should satisfy the following mass-balance relationships:

$$f_{us} + f_{ds} = 100(\%) \quad (6)$$

$$f_{j,us} + f_{j,ds} + f_{j,l} = 100(\%) \quad (7)$$

The PHE removal efficiency during soil washing and coagulation is represented by the parameter $R_j(\%)$.

$$R_j(\%) = f_{j,us} + f_{j,l} \quad (8)$$

The parameter ($R_j, [\%]$) comprises the contribution of the percentage of PHE in the suspended soil particles ($f_{j,us} [\%]$) and the percentage of PHE in the liquid phase of the soil-washing solution ($f_{j,l} [\%]$).

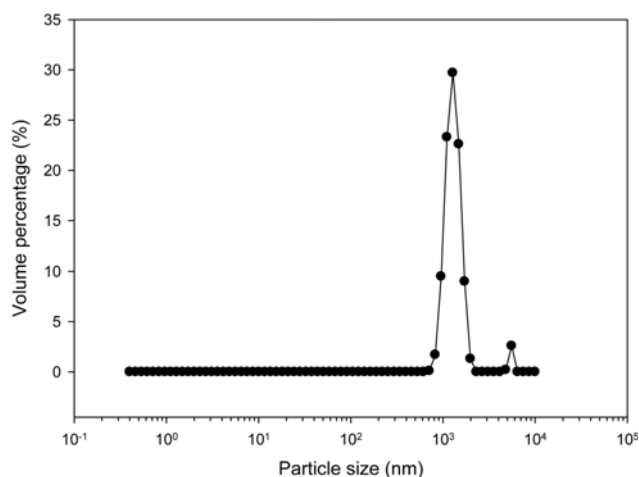


Fig. 2. Particle-size distribution (PSD) of suspended soil particles.

The selective separation factor (SSF) represents the separation of PHE with respect to the separation of soil particles in the system during the soil washing and coagulation process. The SSF parameter reflects the effect of the coagulant on the separation of PHE from soil using a surfactant. The SSF is expressed by the following equation:

$$SSF = \frac{C_{j,us} \cdot C_{us} + C_{j,l}}{C_{j,ds} \times C_{ds}} \times \frac{C_{ds}}{C_{us}} = \frac{f_{j,us} + f_{j,l}}{f_{j,ds}} \times \frac{f_{ds}}{f_{us}} = \frac{R_j}{100 - R_j} \times \frac{R_s}{100 - R_s} \quad (9)$$

The parameter R_s (%) introduced in this equation represents the removal percentage of soil particles after coagulation in the system. A high SSF value indicates a greater degree of PHE separation from the contaminated soil in this process.

3. Soil Properties

The soil sample (BS) was sandy loam containing 48.6% sand, 48.2% silt, and 3.2% clay. The soil was slightly alkaline at pH 8.21 and the organic matter (OM) content of BS was $12.8 \pm 0.09\%$ of total mass of soil sample (Table 1). Because of its relatively high organic-matter content, the soil was expected to have a larger adsorptive capacity for hydrophobic contaminants such as PHE. The dissolved organic matter (DOM) content of BS in DI water was 103.2 ± 18.0 mg/kg. Fig. 2 shows the particle-size distribution (PSD) of the suspended soil particles. This PSD profile indicated that there was little variation in the size of the suspended soil particles and that most of the soil particles were concentrated in the range of 0.8 to 2 μ m, with an average size of 1.3 μ m.

4. Effect of Coagulants on the Removal of Soil

The concentration of TX100 was varied (0.1–20 g/L) in the soil suspension (a constant 5 g/L) during coagulation by various coagulants (CS, PAA, or PAC) to determine the amount of soil removed at different surfactant concentrations. The TX100 concentrations used in this study were varied from below to above the critical micellar concentration (CMC; here, 0.11 g/L), and this concentration range is very similar to TX100 concentrations used for soil-washing processes in practice [29]. As shown in Fig. 3, the percentage removal of soil from the washing solution by coagulation was maximized at a TX100 concentration of 2 g/L. However, further increases in TX100 concentration during soil washing did not yield a further increase in the percentage of soil removed by coagulation but rather

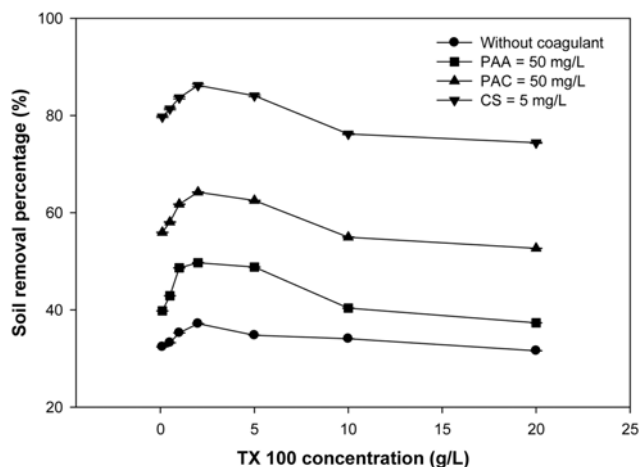


Fig. 3. Removal percentage of soil particles after sedimentation with various coagulants.

decreased soil coagulation. The sedimentation of soil particles from a soil-washing solution with 2 g/L of TX100 without coagulant gave a soil-removal value of 37% after 30 min. The soil-removal values in the washing solutions containing 2 g/L TX100 plus PAA (50 mg/L), PAC (50 mg/L), or CS (5 mg/L) were 50%, 64%, and 86%, respectively, indicating that soil removal was increased by coagulant addition. An earlier study reported that the addition of TX100 to a soil suspension enhanced soil coagulation by CS, PAA, and PAC [15]. The selection of mass based doses of coagulants (CS, PAA, and PAC) in the study was based on our previous work [15], and these chemical compounds were applied at different concentration in the soil-washing solution containing TX100 to show their maximum activity as coagulants. Moreover, the coagulation results indicated that the coagulation of soil from the washing solution could be maximally enhanced by using 2 g/L TX100 and 5 mg/L CS. The coagulation of soil particles from the suspension using CS is due to the combined effects of electrostatic patching and bridging mechanisms [23]. CS showed higher coagulation efficiency than PAA and PAC, even at a concentration 10 times lower, because of its higher charge density than the other coagulants [16]. Therefore, the effective separation of soil particles from a soil-washing solution containing TX100 by CS addition could also improve TX100 recovery after the soil-washing process.

5. Distribution of PHE in Surfactant/Soil/PHE/CS

The extraction of PHE from the contaminated soil by TX100 during the soil-washing process is generally initiated at the CMC and increases with increasing TX100 concentration [8,30]. The concentration of TX100 was varied in the range of 0.1 to 20 g/L in the soil suspension (5 g/L) during soil washing. The total suspended-phase PHE concentration for the system was determined by solvent extraction of PHE from the soil suspension. The values of total suspended-phase PHE concentration for the system with no coagulant increased from 3.24 to 19.4 mg/L with the increase of TX100 concentration from 0.1 to 20 g/L, as shown in Fig. 4(a). The use of PAA (50 mg/L), PAC (50 mg/L), and CS (5 mg/L) as coagulants in the system yielded somewhat increased total suspended-phase PHE concentrations at 5 and 10 g/L TX100 over those without coagulant. In the case of excess addition of TX100 (20 g/L), almost

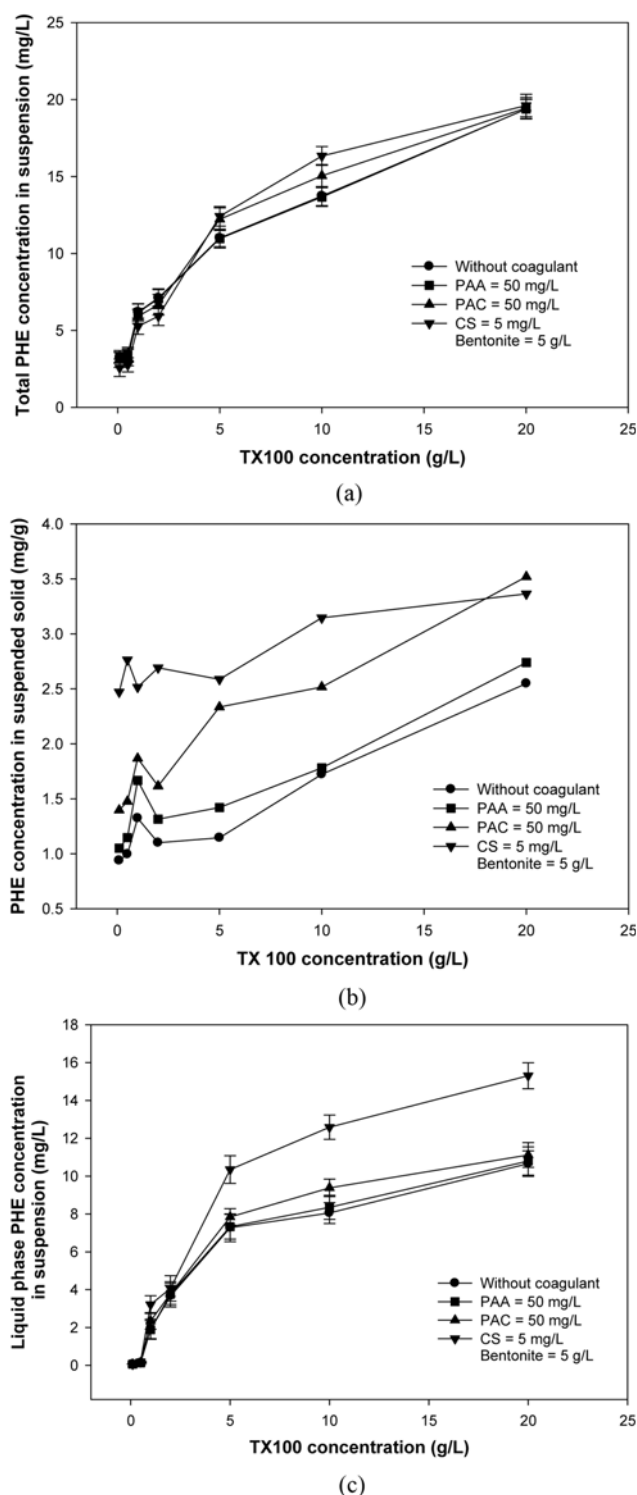


Fig. 4. PHE concentrations in (a) the entire suspension, (b) the solid phase, and (c) the liquid phase in the washing suspension after sedimentation.

all of the PHE (above 98%) was removed whether or not coagulant was used and its effect was not noticeable. Considering that a greater amount of soil particles were removed with the addition of coagulants, the results indicate that PHE concentrations were increased in the liquid and/or suspended-soil phase by the effect of

coagulants.

The PHE concentrations of suspended soil particles after the soil-washing and coagulation processes are shown in Fig. 4(b). The factors determining this concentration are complex because it depends on soil-particle size, the adsorption of surfactant onto the soil particles, and their interactions with the coagulant. The increase of PHE concentration observed with increasing TX100 concentration in the range of 0.1-1 g/L TX100 corresponds to the increase in soil particle removal shown in Fig. 3. This finding was likely due to the removal of larger particles and thus reflects the higher PHE concentrations of the remaining smaller particles. For this reason, the system with no coagulant and a lower soil-removal percentage showed less suspended soil-bound PHE than those with coagulants (CS, PAA, and PAC) at a particular concentration of TX100. The increase of suspended PHE concentration with increasing TX100 concentration was also observed even at high TX100 concentrations. This may be attributable to the increased adsorption of TX100 micelles containing PHE onto soil particles.

Fig. 4(c) reports the liquid-phase PHE concentrations in the soil-washing solutions after coagulation. The liquid-phase PHE concentration in the suspension after sedimentation in the absence of a coagulant increased from 0.07 to 10.7 mg/L with an increase in TX100 concentration from 0.1 to 20 g/L. The systems with PAA (50 mg/L), PAC (50 mg/L), and CS (5 mg/L) showed increases in PHE-solubilization values, going from 0.06 to 10.8 mg/L, 0.07 to 11.1 mg/L, and 0.07 to 15.3 mg/L, respectively, over the same TX100 concentration range. Thus, the addition of coagulants PAA and PAC did not increase liquid-phase PHE concentration in the soil-washing solution using TX100 whereas CS increased PHE solubilization significantly. This finding indicated that the enhancement of PHE solubilization in TX100 mediated soil-washing was likely due to the interaction between CS and TX100 molecules possibly by complex formation [31]. For example, micelle-micelle agglomerations and enlarged interior spaces, loose micelles with low aggregation numbers, or hemimicelles bound to CS may have contributed to the increase in PHE solubilization [31].

6. Removal Efficiency and Selective Separation Factor

The effectiveness of coagulant addition in the surfactant-mediated soil-washing process can be analyzed by several parameters related to the mass distributions of soil and PHE. As shown in Table 3, the maximum value of f_{ds} (%) was observed in the system with 5 mg/L CS as the coagulant, and this value increased in the following order: (no coagulant) < PAA (50 mg/L) < PAC (50 mg/L) < CS (5

Table 3. Distribution of soil and PHE after 30 min sedimentation at 10 g/L TX100

	Without coagulant	PAA (50 mg/L)	PAC (50 mg/L)	CS (5 mg/L)
f_{ds} (%)	34.1	40.4	55.0	76.1
f_{us} (%)	66.0	59.6	45.0	23.8
$f_{j,ds}$ (%)	34.4	31.7	24.8	18.4
$f_{j,us}$ (%)	25.4	26.6	28.4	18.7
$f_{j,l}$ (%)	40.3	41.8	46.9	63.0
R_j (%)	65.7	68.3	75.3	81.7
SSF	0.987	1.46	3.71	14.2

mg/L). Thereby, CS (5 mg/L) was the most effective for coagulation of soil particles from the soil-washing suspension.

The percentage of PHE in the coagulated soil particles ($f_{j,ds}$) was the lowest in the system with 5 mg/L CS and the percentage of PHE in the liquid phase ($f_{j,l}$) was the highest in this system. The maximum R_j (%) value (81.7%) was also found for the system with 5 mg/L CS. These results in the soil-washing and coagulation process indicated that, among the various coagulants tested (PAA, PAC, and CS), CS was the most useful coagulant for enhancing the separation of PHE from the soil-washing solution as well as soil-particle separation. Overall, the R_j (%) values in the cases of coagulant addition were higher than that without coagulant due to the increases in $f_{j,us}$ and $f_{j,l}$, even though the use of coagulant had a negative effect on the PHE removal due to the increase in the amount of PHE partitioned into the sedimented soil.

An SSF value of unity would indicate that PHE and soil were separated to the same degree during sedimentation, whereas SSF values greater than one mean that PHE was more effectively separated than the soil. The SSF values for the systems were found to increase in the following order: (no coagulant) < PAA (50 mg/L) < PAC (50 mg/L) < CS (5 mg/L), with values of 0.987, 1.46, 3.71, and 14.2 for the respective coagulants at 10 g/L TX100. These results clearly show that the application of CS as a coagulant in the soil-washing system can effectively enhance the washing of PAH-contaminated soil with a nonionic surfactant.

As shown in Fig. 5, the variation of the TX100 concentration during soil washing significantly changed the values of R_j (%) and SSF during coagulation with CS. Here the increase in TX100 concentration from 0.1 to 20 g/L increased the R_j (%) and SSF values from 12.9 to 98.1% and from 0.58 to 147, respectively. The extremely high value of SSF at 20 g/L TX100 is because the almost all of the PHE was removed by the addition of excess TX100. Overall, the results indicated that coagulation of soil particles using CS in a TX100 soil-washing solution increased the selective separation of PHE from soil, and thus it improved PHE removal efficiency. Therefore, coagulation by CS may be a promising alternative technology for improving the effectiveness of the remediation of PAH-contaminated soil in practice.

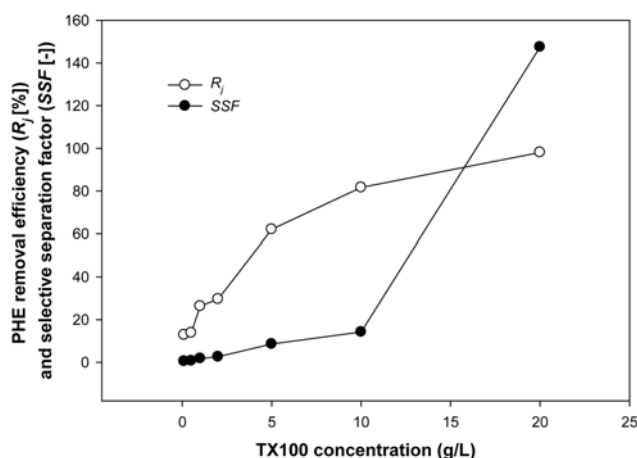


Fig. 5. Effect of surfactant concentration on PHE removal efficiency and selective separation factor during sedimentation with CS coagulant.

CONCLUSIONS

The coagulation of soil particles from a soil-washing solution was investigated using the coagulants CS, PAA, and PAC. CS at a concentration of 5 mg/L was found to be more effective than 50 mg/L of PAA or PAC for the extraction of PHE from soil by TX100 and the coagulation of soil particles from the soil-washing suspension. The factors affecting the distribution of PHE and soil particles in the system with TX100, soil, PHE, and coagulant were very complex, depending on soil size, TX100 and/or coagulant adsorption, and PHE solubilization. The maximum removal efficiency of PHE (R_j) and the maximum value of the selective separation factor (SSF) were achieved using CS as the coagulant, which acted mainly by enhancing PHE solubilization in the washing solution by increasing the coagulation of soil particles.

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