

Application of surfactant solutions and colloidal gas aphon suspensions in flushing naphthalene from a contaminated soil matrix

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Abstract

The applicability of conventional surfactant solutions and colloidal gas aphon (CGA) suspensions to remove naphthalene from a contaminated soil matrix was investigated. Laboratory studies were conducted to evaluate the relative suitability of nonionic, cationic and anionic surfactants in removing naphthalene from the soil. Nonionic surfactant was found to be more efficient than the ionic surfactants in removing naphthalene from contaminated soil matrix in batch experiments and was selected for further flushing studies. The presence of surfactant reduced the volatilization of naphthalene. Micellar solubilization appears to be the primary mechanism of removal using both surfactant solutions and CGA suspensions. Increasing the concentration of the surfactant solution enhanced the percent removal of naphthalene. Using a CGA suspension as a flushing medium may result in channeling and pore clogging in the soil matrix, thereby affecting the overall efficiency of the process.

1. Introduction

Contamination of subsurface soil by toxic and hazardous chemicals is a major environmental problem. These contaminants are often released into the soil or groundwater system from abandoned waste sites, accidental spills, and industrial effluents. Most of the contaminants are carcinogenic and mutagenic in nature and, depending on their fate and transport, may pose serious threat to human health and environmental quality. Naphthalene is a low molecular weight, polycyclic aromatic

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hydrocarbon (PAH), commonly found in association with petroleum wastes. This hydrophobic organic compound is one among the 16 PAHs on the USEPA list of priority pollutants to be monitored in industrial effluents [1].

Most of the contaminants are hydrophobic organic compounds, nonpolar, and nearly insoluble in water because of their inability to compete with the strong hydrogen bonds between water molecules [2]. These compounds are adsorbed to soils and sediments, and hence soil remediation depends on the ability to desorb them from the soil and to incorporate them in the bulk aqueous phase. Conventional pump-and-treat technology for removing contaminants has been limited to in situ water flushing. Flushing with water alone may take decades to achieve the desired level of removal [3]. More cost-effective methods are needed to clean up sites that are contaminated with hydrophobic organic compounds. The feasibility of one such method using aqueous surfactant solutions and CGA suspensions for flushing naphthalene from soil was assessed in this study.

When amphiphilic surfactants are dissolved in water, micelle formation occurs at a particular concentration known as critical micelle concentration (CMC). Micelles are composed of individual amphiphiles with their hydrophilic moieties in contact with the aqueous phase and their hydrophobic moieties grouped into the interior of the aggregate. Micelles due to their hydrophobic interiors, known as hydrocarbon cores, solubilize hydrophobic organic compounds, which are otherwise insoluble or sparingly soluble in water.

As there are different types of surfactants available, it is necessary to evaluate the relative suitability of a surfactant to flush a target contaminant from the soil or aquifer systems. Assessment of a surfactant can be based on several properties, viz. solubility, adsorption, critical micelle concentration, soil colloid dispersion, biodegradation, soil flushing ability, etc. The scope of this study for selecting a suitable surfactant for flushing naphthalene from the soil is limited to solubility and adsorption.

An innovative technology that can be applied to flush hydrophobic organic contaminants from soil is the use of colloidal gas aphron (CGA) suspensions. Colloidal gas aphrons were first described by Sebba [4]. They are micro gas bubbles classified as *kugelschaums*, encapsulated by a thin soap film containing 65% of air by volume. They are a dispersion of micro bubbles in water with diameters between 25 and 150 μm . CGA bubbles have the same charge as the surfactant from which it is generated. Fundamental properties and applications of CGA have been extensively studied [5] and applications of CGA suspensions in soil flushing have been reported by Longe [6] and Roy et al. [7, 8].

The specific objectives of this research are (i) to assess the relative suitability of nonionic, anionic and cationic surfactants to remove naphthalene from a contaminated soil matrix and (ii) to evaluate the potential of surfactant solutions and CGA suspensions in removing naphthalene from the soil matrix.

2. Materials and methods

2.1. Chemicals

The hydrophobic organic compound, naphthalene, was purchased from Aldrich Chemical Co. (Milwaukee, WI). Its molecular formula is $C_{10}H_8$. Physical and chemical properties of naphthalene are listed in Table 1. The surfactants used were Tergitol (Sigma Chemical Co., MO), sodium dodecyl sulfate, SDS (Life Tech Inc., MD) and hexadecyltrimethyl ammonium bromide, HTAB (AMRESCO, OH). Molecular formulas and properties of surfactants are presented in Table 2.

2.2. Soil

The soil used in this study was a fine silty loam. Fine sandy soil and clay soil were dried separately in an oven overnight at 105°C . Big lumps were crushed and pulverized. The sandy soil and clay soil were mixed in 9:1 proportion by weight and passed through a 2 mm sieve. Physical and chemical properties of the soil are given in Table 3.

2.3. Solubility experiments

Batch experiments were performed at room temperature (22°C) to determine the naphthalene solubility in nonionic, cationic and anionic surfactants. For each surfactant, six concentrations were selected and solutions were prepared by adding 1 g of

Table 1
Physical and chemical properties of naphthalene

Molecular weight	128.17
Boiling point (760 mmHg) ($^\circ\text{C}$)	217.9
Melting point ($^\circ\text{C}$)	80.2
Log octanol/water partition coefficient	3.36
Water solubility (25°C) (mg/l)	31.7
Henry's law constant ($\text{atm m}^3/\text{mol}$)	4.83E-4

^a Source: Ref. [22].

Table 2
Molecular formula and properties of surfactants used

Surfactant	Molecular formula	MW	CMC	Charge
Tergitol	$C_{11-15}H_{23-31}O(C_2H_4O)_n$	738	0.15	Nonionic
HTAB	$CH_3-(CH_2)_{15}-N^+(CH_3)_3Br^-$	364.09	0.9	Cationic
SDS	$CH_3-(CH_2)_{11}-OSO_3^-Na^+$	288.38	8.08	Anionic

MW = molecular weight; CMC = critical micelle concentration at 25°C expressed in mM.

Table 3
Physical and chemical properties of soil

Physical		Chemical	
Sand	70%	Sodium	24 mg/kg of soil
Silt	15%	Calcium	1084 mg/kg of soil
Clay	15%	pH	6.6
Organic matter	0.11%	CEC	8.0 meq/100 gm

naphthalene to 500 ml of the surfactant solution. This solution was stirred for 24 h to allow naphthalene to equilibrate with the surfactant solution. The resulting solution was centrifuged, filtered and analyzed for naphthalene using HPLC. Solubility studies were done in duplicate for each surfactant.

2.4. Adsorption experiments

Batch adsorption studies were performed in 125 ml flasks containing 100 ml of surfactant solution (50 mM concentration) containing different concentrations of naphthalene ranging from 75 to 200 mg/l. 5 g of soil was used in each flask. Flasks were agitated on a shaker table for 48 h and the concentration of naphthalene in the aqueous solution was monitored at regular intervals for 48 h.

2.5. Soil contamination and column packing

Naphthalene was dissolved in 200-proof ethyl alcohol and added to the soil. The mixture was vigorously shaken for 10 min to obtain uniform distribution of naphthalene in soil [9]. The wet soil mixture was placed in a hood and ethyl alcohol was allowed to evaporate overnight. The spiked soil was analyzed for naphthalene concentration before using it.

A schematic representation of the experimental setup for soil flushing experiments is shown in Fig. 1. The contaminated soil was packed in a glass column with stainless steel top and bottom fittings. The glass column used was 10 cm long and of 5.9 cm inner diameter. A filter stone (Soil Test Co.) was placed at the bottom of the column and the soil was packed in four layers with each layer containing 100 g of soil. Each layer was compacted by giving 25 blows with a compacting rod to obtain a bulk density of 1.54 g/cm³ and a porosity of 0.42. The top 1 cm of the glass column was filled with 35 gm of coarse sand followed by a coarse wire mesh and a fine wire mesh to provide uniform distribution of the flushing solution into the column and prevent possible channeling. The hydraulic conductivity values for the packed soils ranged from 3.2×10^{-4} to 3.9×10^{-4} cm/s.

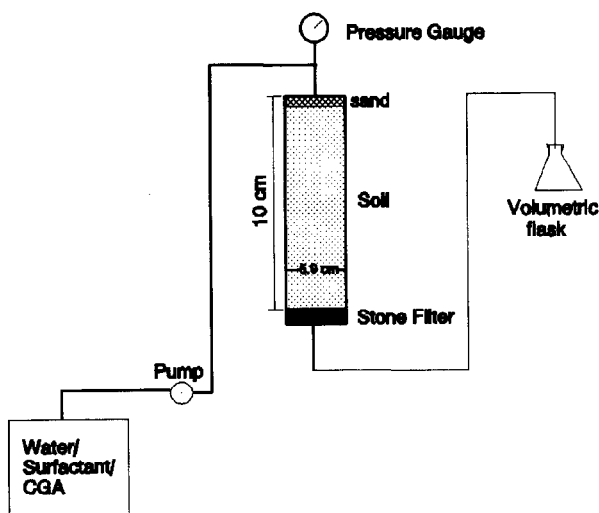


Fig. 1. A schematic diagram for 1-D soil flushing experiments.

2.6. Soil flushing experiments

Preliminary column experiments were conducted using three different surfactant solutions, i.e., Tergitol, HTAB and SDS each of 50 mM concentration. The flushing solution was pumped into the saturated soil column to provide wash in a downflow mode at a rate of 2.6 ml/min. The surfactant solution which was most efficient in removing naphthalene from soil was selected for further studies.

The selected surfactant was used at 0.15, 20 and 50 mM concentrations for further flushing studies. Column experiments were conducted with conventional surfactant solutions and CGA suspensions generated from the selected surfactant solutions. The CGA suspensions were generated using a unit fabricated in our laboratory [10]. The pressure drop across the soil column was monitored along with the time of collection for each pore volume.

2.7. Measurement of vapor–liquid partitioning constant (H^*)

The procedure used is a modification of the method called EPICS (equilibrium partitioning in closed systems) that has been extensively used for measurement of Henry's law constant for volatile organic compounds. This method is similar to the method described by Valsaraj et al. [11] except that, instead of vapor samples, aqueous samples in the flasks were analyzed for naphthalene concentration. Experiments were conducted in 150 ml flasks sealed with septum caps. The samples were prepared with water and with varying concentrations of Tergitol (0.15, 20 and 50 mM) combining a known amount of naphthalene. The flasks with 135 ml aqueous volume

were sealed with septum caps and equilibrated at 23 °C. After 24 h of equilibrium, the aqueous samples from the flasks were analyzed for naphthalene.

2.8. Analysis of naphthalene

The concentration of naphthalene in aqueous samples was measured using a high-pressure liquid chromatograph (Hewlett Packard series 1050). An Envirosep-PP packed column (Phenomenex Co., Torrance, CA, 125 cm length and 3.2 mm diameter) was used. The UV absorbance of naphthalene was monitored at a wavelength of 272 nm. The HPLC analytical procedure was based on the method provided by the column manufacturer. Aqueous effluent from the soil flushing experiments was centrifuged for 10 min at 14 000 rpm (Brinkmann centrifuge model 5415) and filtered through a 0.45 µm PTFE syringe filter (Nalge Co., Rochester, NY) before HPLC analyses. Analyses of naphthalene in the solid phase for batch adsorption and column flushing experiments were performed by adding 5 g of contaminated soil to a flask containing 100 ml of acetonitrile and the flasks were kept agitated on a shaker table overnight. Naphthalene partitioned into the solvent phase was measured using HPLC.

3. Results and discussion

3.1. Solubility of naphthalene

Experimental results of solubility of naphthalene in Tergitol, HTAB, and SDS are shown in Fig. 2(a)–(c). Aqueous-phase concentration of the solubilized naphthalene is plotted as a function of the surfactant concentration for each data set. These plots show the relationship between the apparent naphthalene solubility and the surfactant concentration. This linear relationship can be expressed by the following equation:

$$S_{\text{mic}} = S_{\text{CMC}} + \text{MSR}(C_{\text{surf}} - \text{CMC}),$$

where S_{mic} is the total apparent solubility of naphthalene in moles per liter of micellar solution at a particular surfactant concentration greater than CMC, S_{CMC} is the apparent solubility of naphthalene in moles per liter at CMC, C_{surf} is the surfactant concentration in moles per liter and MSR is the molar solubilization ratio.

MSR is defined as the number of moles of organic compound solubilized per mole of surfactant added to solution [12]. It is a measure of the effectiveness of a particular surfactant in solubilizing a given solute. It is slope of the line that results when corresponding surfactant concentrations are plotted against the naphthalene concentrations.

The solubilizing power of micelles of a particular surfactant can be expressed as a micelle-phase/aqueous-phase partition coefficient, K_m [13]. K_m is the ratio of the

Fig. 2. Solubility of naphthalene using different surfactant solutions.

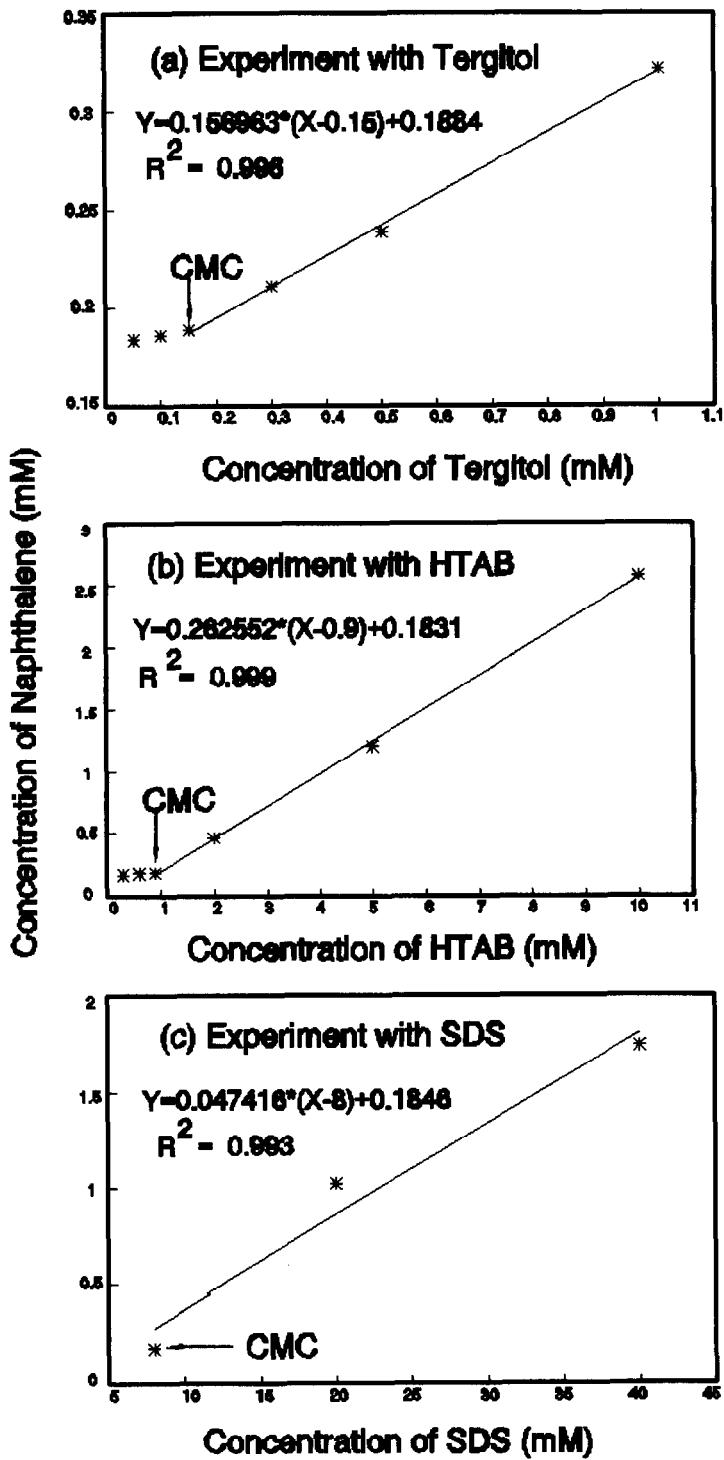


Table 4
Micelle–water partition constants for naphthalene

Surfactant	MSR	log K_m
Tergitol	0.1569	4.6046
HTAB	0.2625	4.8408
SDS	0.0474	4.1373

mole fraction of the compound in the micellar pseudophase, X_m , to the mole fraction of the compound in the aqueous phase, X_a . It can also be calculated from the MSR as follows:

$$K_m = (55.4/S_{CMC}) [MSR/(1 + MSR)].$$

Table 4 shows the calculated values of MSR and log K_m for the three different surfactants. The log K_m value for naphthalene in Tergitol is in the same range as reported by Edwards et al. [14]. The slope of the line, i.e. the MSR obtained in this study for solubility of naphthalene in SDS (Table 4), is comparable to that reported by Gannon et al. [9].

It was found that with an increase in concentration of surfactant, the amount of naphthalene solubilized in the solution also increased. Above the CMC an increase in concentration of the surfactant solution results in a larger number of micelles formed. Hence the solubilization of naphthalene in the micellar phase also increases. Solubilization of nonpolar compounds also tends to increase with an increase in the concentration of the compound. This is due to the fact that as more solubilize is incorporated in the core of the micelle, the core becomes more like the solubilize resulting in an increase in the solubilizing capacity of the core [15].

At low surfactant concentrations (< 1 mM), solubility of naphthalene in Tergitol is better than that in other surfactants due to the low CMC for Tergitol. At higher concentrations, naphthalene solubility in HTAB is higher than that in other surfactants which may be due to the fact that HTAB is a 16-carbon chain surfactant while SDS is only a 12-carbon chain surfactant. It is well known that the longer the hydrophobic chain length, the solubilizing capacity of the micelle [16]. The lower solubilizing power of the anionic surfactant may be due to a dense packing of the surfactant molecules in the micelles [17].

3.2. Adsorption of naphthalene

Adsorption of naphthalene on soil from the aqueous phase with surfactants was monitored for 48 h and the change in the concentration as a function of time is presented in Fig. 3(a)–(c) for Tergitol, HTAB and SDS. In the presence of all the three surfactants, aqueous concentration of naphthalene changed very little after the first sampling point. An apparent equilibrium concentration of naphthalene in surfactant solution was achieved in about 8 h. The adsorption of naphthalene on soil in the

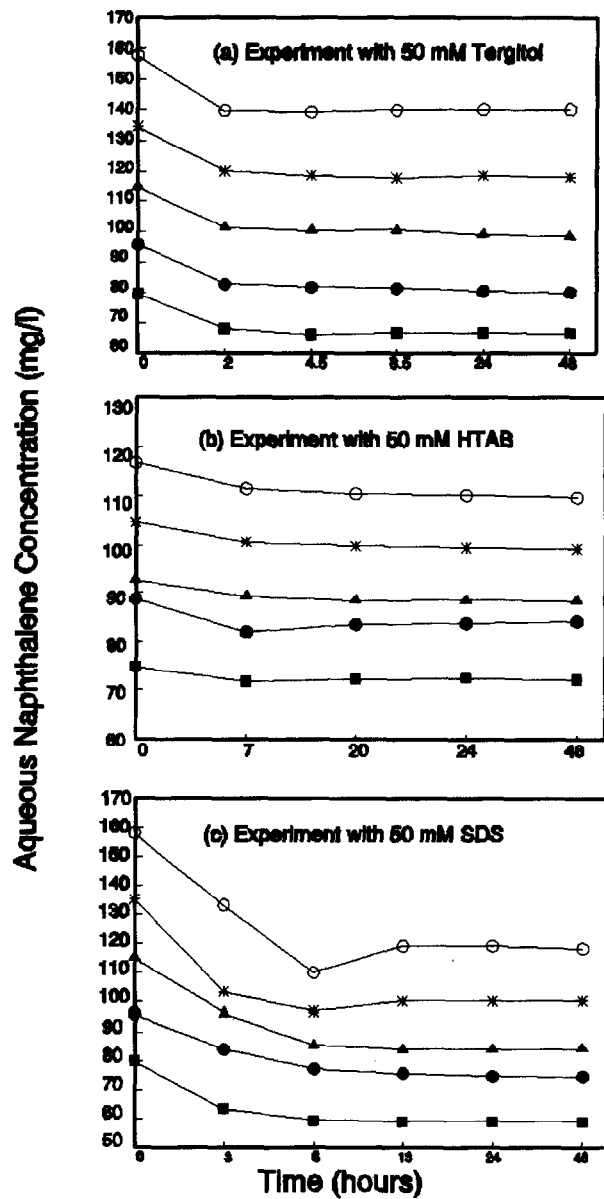


Fig. 3. Influence of type of surfactant and initial naphthalene concentration on the adsorption of naphthalene on soil.

presence of Tergitol, HTAB and SDS solutions ranged from 0.13 to 0.79 mg per gram of soil.

The equilibrium isotherms (i.e. mass of naphthalene adsorbed per mass of soil versus the equilibrium aqueous concentration of naphthalene) in the presence of all

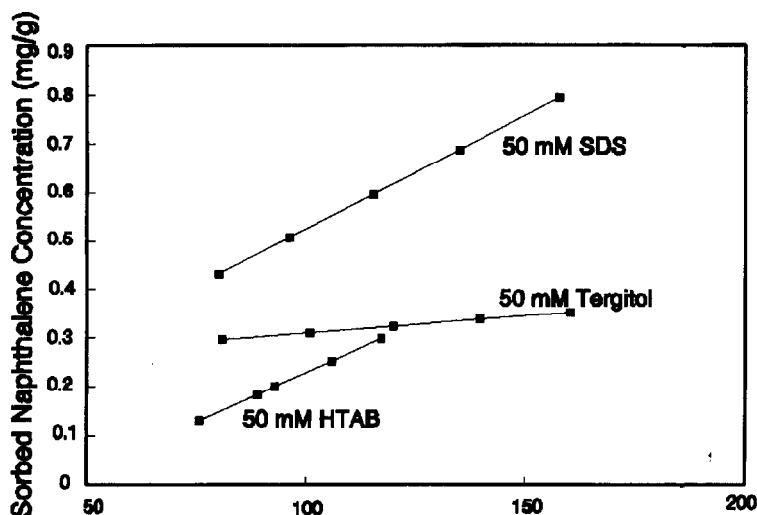


Fig. 4. Naphthalene sorption isotherm in the presence of different surfactants.

the three surfactants (Tergitol, HTAB and SDS) are shown in Fig. 4. The adsorption isotherms are linear in the naphthalene concentration range tested. Similar adsorption isotherms have been reported by Palmer et al. [18] for other nonionic organic compounds.

From the isotherms, the adsorption of naphthalene on soil in the presence of HTAB is observed to be lower than that in the presence of Tergitol and SDS. The differences in adsorption of naphthalene on soil in the presence of different surfactants may be related to the ability of these surfactants to solubilize naphthalene. Since 50 mM concentration of HTAB solution has a high solubilization capacity, naphthalene would be found to have less concentration on the soil grains. On the contrary, the high adsorption of naphthalene on the soil in the presence of SDS may be due to the weak affinity of naphthalene molecules for the surfactant molecules. As the solubility in aqueous surfactant decreases, the potential for naphthalene to get adsorbed on to the soil grains is also expected to increase.

The slope of the isotherm is referred to as the linear partition coefficient (K_d). The soil–water partition coefficient, K_{oc} , values were computed using K_d and organic carbon content of the soil. The adsorption of naphthalene on soil in the presence of HTAB is lower than that in the presence of other surfactants. However, a comparison of the values of the K_{oc} for naphthalene shows that the lowest value of 645 was obtained using Tergitol. The value of K_{oc} with HTAB as a surfactant was 4309.

3.3. Soil flushing experiments

Preliminary column experiments were performed with Tergitol (nonionic), HTAB (cationic) and SDS (anionic) to select a surfactant based on its ability to remove

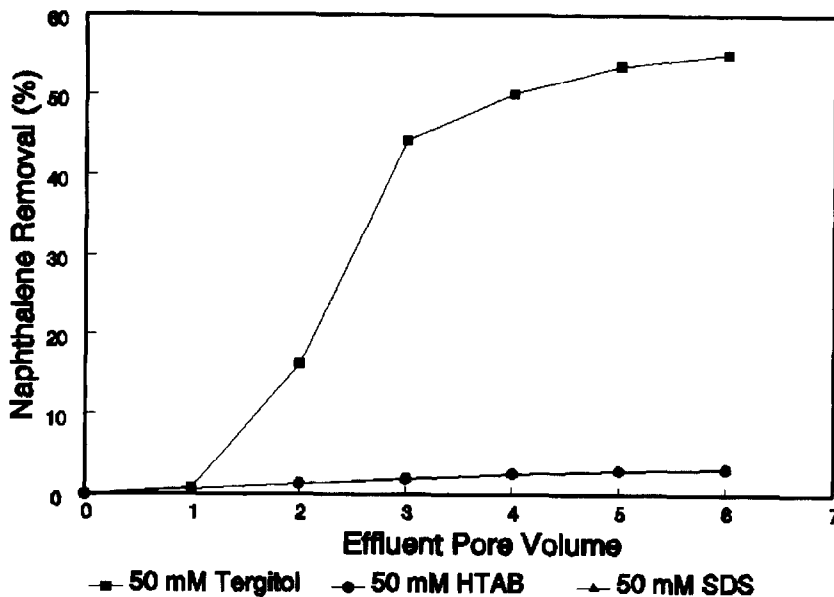


Fig. 5. Comparison of naphthalene removal from preliminary column runs with three different surfactant solutions.

naphthalene from the soil matrix. Soil columns were saturated with deionized water before conducting any run. All the surfactant solutions used were of 50 mM concentration. The percent removals of naphthalene using Tergitol, HTAB and SDS were 55%, 3% and 3%, respectively (Fig. 5), after six pore volumes.

The use of a cationic surfactant (HTAB) decreased the percentage removal by 20 times as compared to a nonionic surfactant, Tergitol. Cationic surfactants have positive charges and are adsorbed strongly to soils which are usually negatively charged. Even though the solubilizing capacity of HTAB is comparatively high, one can expect less removal efficiency because of the strong complexation of cationic surfactants with soil particles.

SDS is the least preferred surfactant among the three surfactant solutions tested for two reasons. The solubilizing power of SDS is considerably lower than that of the other surfactants whereas the adsorption of naphthalene on soil in the presence of SDS is relatively high. Moreover, if clay content is more than 10% (soil used in the experiments contained 15% clay), cation exchange takes place between soil and Na^+ leading to the release of Ca^{2+} and precipitation of $\text{Ca}(\text{DS})_2$. This precipitation has been observed to reduce the hydraulic conductivity of the soil matrix that leads to less removal of the contaminant [19].

The percent removal of naphthalene observed from the preliminary column studies indicate that Tergitol is the most effective of all the surfactants tested. The adsorption isotherms show that adsorption of naphthalene onto the soil in the presence of

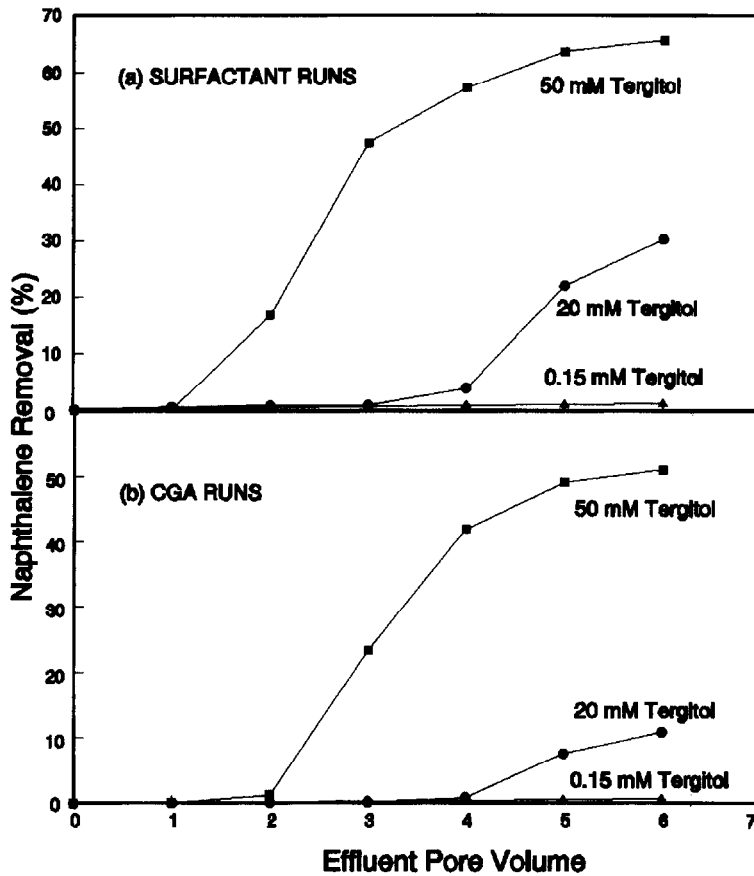


Fig. 6. Comparison of naphthalene removal using different concentrations of surfactant solutions and CGA suspensions.

Tergitol is less compared to that in the presence of HTAB and SDS. Also Tergitol has a low CMC and is biodegradable [20], which makes it the best choice for flushing naphthalene from the contaminated soil. In view of this, further studies were conducted using Tergitol to evaluate its efficiency in removing naphthalene from the soil matrix.

To study the effect of concentration of the Tergitol on naphthalene removal, three concentrations at and above CMC (0.15, 20 and 50 mM) were selected. The percent removals of naphthalene using 0.15, 20 and 50 mM Tergitol, in six pore volumes, were 3%, 30% and 66%, respectively (Fig. 6(a)). For each run, a mass balance on naphthalene was performed by quantifying the amount of naphthalene present in contaminated soil before packing the column, total removal from the aqueous effluent and the amount remaining in the soil after flushing the column with surfactant solution. The mass balance for naphthalene from the surfactant runs ranged from 73% to 81%.

The amount of naphthalene removed in the first pore volume in all the runs was relatively low. This observation is to be expected as the solubility of naphthalene in water is low and the first pore volume of surfactant solution just displaces the water filled in the pore spaces of the soil column. For a low surfactant concentration, i.e. at CMC (0.15 mM), naphthalene removal increased linearly at a small rate with each pore volume. In six pore volumes the total removal of naphthalene was 3%. Experimental results show that effective removal of naphthalene cannot be obtained at or below the CMC. In the case of 20 mM Tergitol, only 4% of removal was observed in the first four pore volumes. However, in the fifth pore volume the removal increased to 18%. When 50 mM concentration of Tergitol was used, about 16% and 31% of removal was obtained in the second and third pore volume, respectively. From the fifth pore volume there was a gradual decrease of naphthalene concentration in the effluent.

CGA suspensions were generated with 0.15, 20 and 50 mM concentrations of Tergitol solutions. The removal in aqueous phase is the cumulative percentage of naphthalene removed in six pore volumes of effluent. Fig. 6(b) shows that the removal of naphthalene from the soil using CGA suspension follows the similar pattern as observed while using the surfactant solutions. The percent removal of naphthalene in six liquid pore volumes of CGA was 1%, 11% and 51% with CGA solutions generated from 0.15, 20 and 50 mM Tergitol solutions. CGA suspensions are made up of surfactant and water, containing 65% of air by volume. There are three phases to be considered in the case of CGA suspension, viz. the aqueous phase, micellar phase and gas phase. Since naphthalene is a semivolatile compound, some removal of naphthalene should be possible by partitioning into the air phase of CGA suspensions as well as in the aqueous phase.

In order to elucidate whether the percent removal of naphthalene in the gas phase of CGA was of significance, the vapor–liquid partitioning constant, H^* , was measured for naphthalene in the laboratory in the presence of water and in the presence of different concentrations of Tergitol (0.15, 20 and 50 mM). Aqueous-phase concentration of naphthalene in the flasks was measured before and after equilibrium. The difference between the two gives the equilibrium vapor-phase concentration of naphthalene. At equilibrium H^* was calculated using the following equation:

$$C_g = H^*C_{aq},$$

where C_g is the concentration in the gas phase (mg/l), C_{aq} is the concentration in the aqueous phase (mg/l) and H^* is the vapor–liquid partitioning constant (dimensionless). As seen from the values of H^* in Table 5, upto the CMC (0.15 mM) there is no significant change in H^* whereas at 20 and 50 mM concentrations of Tergitol, the value of H^* decreases by 30% and 46%, respectively. Similar observations were also noted for aromatic compounds in the presence of nonionic surfactant [21]. These results show that, in the presence of Tergitol, volatilization of naphthalene is significantly reduced.

Let us assume that equilibrium is maintained between the aqueous phase, micellar phase and gas phase of CGA suspension in the column. Since the H^* value for different surfactant concentrations and the concentration of naphthalene in aqueous

Table 5
Change in vapor–liquid partitioning constant with surfactant concentration

Naphthalene solution with	H^* [(mg/l)/(mg/l)]
Water	0.048
0.15 mM Tergitol	0.047
20 mM Tergitol	0.034
50 mM Tergitol	0.026

effluent (C_{aq}) was known, the amount of naphthalene removed in the gas phase (C_g) of the effluent was calculated using the same equation mentioned above. It was found that the naphthalene removed in the gas phase of CGA, generated with three different surfactant concentrations, was negligible.

Comparing the rate of removal of naphthalene using 20 and 50 mM Tergitol as CGA suspensions, it can be observed that the higher the surfactant concentration the larger the removal of naphthalene from the soil matrix. The amount of naphthalene removed in six pore volume shows that increasing the surfactant concentration enhances the percent removal of naphthalene. The effective flushing of naphthalene from the soil can be explained by the increased solubility of naphthalene in the surfactant micelles. With increase in concentration of the surfactant, the number of micelles formed in the surfactant solution increases. A hydrophobic compound like naphthalene has an affinity towards the hydrophobic interior of the micelle. It is entrapped in the micelles and washed away easily from the soil matrix. This indicates that micellar solubilization is the primary mechanism responsible for the removal of naphthalene from the contaminated soil using surfactant solution.

When the overall performance of the conventional surfactant solutions and CGA suspensions was compared it was observed that the percent removal of naphthalene with CGA was lower than that by surfactant solutions. The reasons for the low removal are believed to be channeling and pore clogging due to dispersion of soil colloids by CGAs. Channeling was observed from the fourth pore volume of the CGA runs. It was observed that after the fifth pore volume the flow rate of effluent was considerably reduced at 50 mM concentration. This is due to pore clogging in the soil matrix. The pore spaces between the grains get clogged due to dispersion of colloids and there will be a decrease in the hydraulic conductivity of the soil matrix in that region, which in turn reduces the volume of flushing solution passing through the soil matrix. The reduction in the rate of flow of CGA suspension passing through the contaminated soil reduced the removal of naphthalene from soil. Due to channeling, the CGA suspension bypasses the zones of soil contaminated with naphthalene and passes through removing only naphthalene accessible to solution in large pores.

A pressure gauge was connected to the influent end of the column to monitor the pressure drop across the soil column. Fig. 7(a) shows the variation in pressure for the surfactant runs. For a 0.15 mM concentration of conventional surfactant solution, the

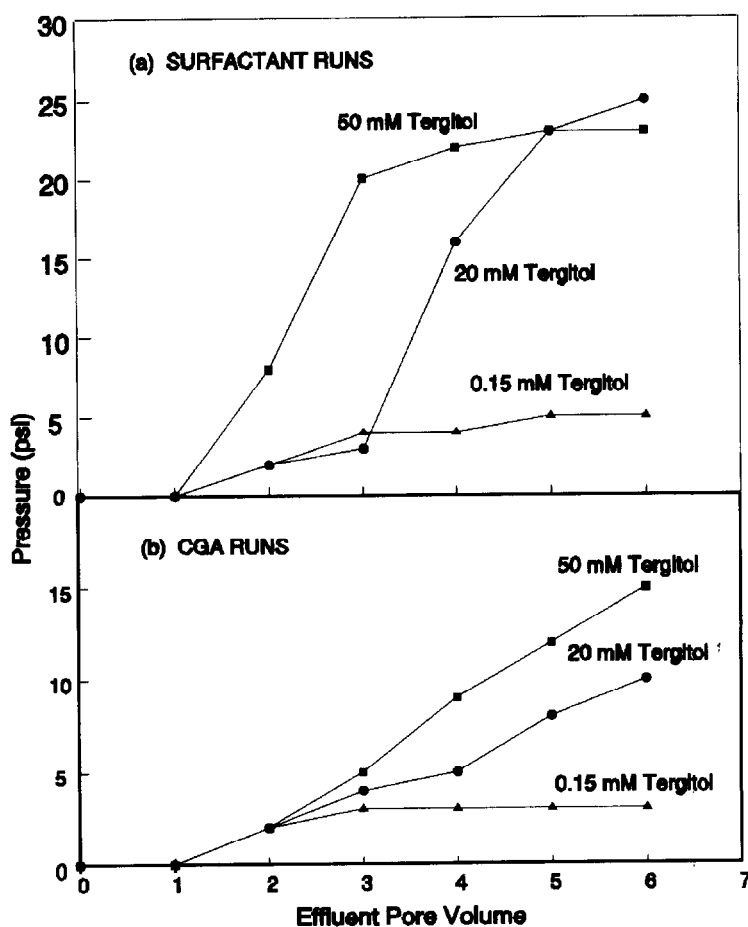


Fig. 7. Comparison of pressure buildup using surfactant and CGA runs.

pressure increased gradually up to 5 psi by the fifth pore volume and remained stable for the rest of the run. In the case of higher concentrations of Tergitol (20 and 50 mM), the pressure gradually increased up to 25 psi. As can be seen from Fig. 7(b) the pressure in the case of CGA flushing experiments increased up to 15 psi in six pore volumes. Even though the overall pressure buildup in CGA runs was less than that in surfactant runs, in CGA runs the pressure continued to increase considerably with each pore volume. This increase in pressure when using CGA suspension was due to clogging of the soil pores due to dispersion of colloids. This pore clogging, as mentioned earlier, reduces the flow of flushing solution through the contaminated area decreases the efficiency of naphthalene removal from the type of soil matrix used in this study.

4. Conclusions

The following conclusions can be drawn based on the results of this research on the application of surfactant solutions and colloidal gas aphrons in flushing naphthalene from a contaminated soil matrix:

- The naphthalene aqueous solubility in HTAB solutions is higher than in Tergitol and SDS solutions.
- Adsorption isotherms for naphthalene on soil were linear in the presence of all three surfactants tested. The adsorption of naphthalene is less in the presence of Tergitol than that in the presence of HTAB and SDS.
- From the preliminary column studies, the nonionic surfactant Tergitol was found to be more suitable for flushing naphthalene from soil than the ionic surfactants HTAB and SDS.
- As the surfactant concentration increased, the percent of naphthalene removed from the soil also increased using both surfactant solutions and CGA suspensions.
- Volatilization of naphthalene decreases with increase in concentration of nonionic surfactant Tergitol.

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