

# Cationic Surfactant Feasibility for Use in Removal of Lead from Soil

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## ABSTRACT ●

The feasibility of using cationic surfactants to desorb lead (Pb) from contaminated soil was investigated by a two-phase batch-test program. In phase I, Pb desorption from the Slaughterville sandy loam was measured as a function of surfactant concentration for 10 cationic surfactants. In Phase II, Slaughterville sandy loam and Teller loam soils were used to measure the impact of pH on surfactant desorption of Pb. During this part of the investigation, pH was varied over the range of 4 to 9, while the initial surfactant concentration was kept constant at 0.025 mole/L.

Phase I results indicate that 3 of 10 screened surfactants, Iso-stearamidopropyl Morpholine Lactate (ISML), Lapyrium Chloride (LC), and Dodecyl Pyridinium Chloride (DPC), are clearly better in desorbing lead. At solution concentration of 0.1 mole/L, ISML, LC, and DPC desorbed 82, 59, and 50% of Pb, respectively, from Slaughterville sandy loam. Data from phase II show that Pb desorption by 0.025 mole/L surfactant solutions is pH dependent. As pH decreased, desorption of lead increased. At a pH of 4, ISML, LC, and DPC desorbed 83, 78, and 68% Pb, respectively, from Slaughterville sandy loam along with 36, 32, and 29% Pb, respectively, from Teller loam. These test results support the feasibility of using cationic surfactants in the removal of lead and other heavy metals from fine-grained soil.

**Key Words:** cationic surfactant, lead desorption, soil batch equilibrium, cation exchange.

## INTRODUCTION ●

Heavy metal-contaminated soil is one of the most common problems constraining cleanup at hazardous waste sites across the country; the problem is present at >60% of the sites on the United States Environmental Protection Agency (EPA) National Priority List (USEPA, 1992). Leachate and runoff from soils contaminated by heavy metals potentially degrade ground and surface waters, while wind erosion tends to spread contamination over large areas. Present technologies for in situ environmental remediation of met-

als from soil are costly and often ineffective. The metals most often encountered include lead, chromium, arsenic, cadmium, copper, and zinc. The EPA determined that the greatest need for new remedial technologies in the Superfund Program is for heavy metals in soil (USEPA, 1993), since existing remediation technologies are considered too expensive and often ineffective. Of the heavy metals, lead (Pb) tends to be the least mobile in the soil environment (McBride, 1994) and therefore was chosen for testing in our study. The high toxicity of Pb makes its presence in the environment a significant health risk to animals and humans. Materials with Pb contamination include municipal solid wastes, sewage sludge, industrial by-products, and wastes from mining and smelting operations (Pierzynski et al., 1994). Pb levels in sewage sludge-treated soils are considerably higher than levels in most natural soils because of the relatively high concentration of Pb from industries such as battery manufacturing (Moore and Ramamoorthy, 1984; McBride, 1994). In soil, Pb solubility increases with decreasing pH. As pH falls, most Pb-containing minerals become less stable, and mineral and organic matter surface functional groups promote Pb desorption due to charge reversal. These processes are significant at pH values below 5.5.

The concept of using surfactant solutions for environmental soil flushing originated with testing in the petroleum industry for enhanced oil recovery. Sabatini et al. (1995) determined that surfactant-based technologies have the potential to significantly enhance subsurface remediation of such chlorinated solvents as PCE and TCE by using pump-and-treat procedures. Saturated soil column flushing tests by Ang and Abdul (1991) and Ducreux et al. (1990) showed the feasibility of using surfactants to mobilize residual hydrocarbons. Pilot tests conducted by Abdul and Ang (1994) indicate the effectiveness and efficiency of using surfactants to flush organic contaminants from unsaturated sediments under typical field conditions. To provide guidance for surfactant selection and determination of realistic remediation goals using surfactant-enhanced technology, Fountain et al. (1995) studied enhanced removal of dense nonaqueous-phase liquids by using surfactant field trials. The effect of surfactants on

TABLE 1. Surfactants used.

Surfactant Chemical Name	Abbreviation	Chemical Formula	Source
Polyoxypropylene methyl diethyl ammonium chloride	PMDAC-1	$[(C_2H_5)_2CH_3N(C_3H_6O)_{6.3}H]Cl$	WITCO
Polyoxypropylene methyl diethyl ammonium chloride	PMDAC-2	$[(C_2H_5)_2CH_3N(C_3H_6O)_{24.6}H]Cl$	WITCO
Polyoxypropylene methyl diethyl ammonium chloride	PMDAC-3	$[(C_2H_5)_2CH_3N(C_3H_6O)_{40.1}H]Cl$	WITCO
Propoxyl diethylethanolammonium ethanol phosphate	PDEP	"Formula not available"	WITCO
Lapyrium chloride	LC	$[C_{11}H_{23}C_3O_2H_5NC_2ONC_5H_5]Cl$	WITCO
Dodecyl trimethyl ammonium bromide	DTAB	$[C_{12}H_{25}N(CH_3)_3]Br$	Aldrich
Dodecyl pyridinium chloride	DPC	$[C_{12}H_{25}NC_5H_5]Cl$	Aldrich
Domiphen bromide	DB	$[C_{12}H_{25}N(CH_3)_2(C_2H_4OC_6H_5)]Br$	Aldrich
Isostearamidopropyl morpholine lactate	ISML	$C_{25}H_{50}N_2O_2 \cdot C_3H_6O_3$	WITCO
Tetradecyl trimethyl ammonium bromide	TTAB	$[C_{14}H_{29}N(CH_3)_3]Br$	Aldrich

hydraulic properties of both saturated and unsaturated soils has been investigated by Allred and Brown (1995).

Surfactants also have shown potential for environmental remediation of heavy metals from soil, although research in this area has been limited. Cationic surfactants can be used to modify soil surfaces to promote displacement of metal cation from solid to liquid phase. They cause the transfer of the soil-bound metal to the liquid phase through ion exchange. This process of desorption and mobilization of previously adsorbed metal cations on negatively charged soil surfaces may be applied to in situ soil remediation. Boucharde et al. (1988) determined that a cationic surfactant could effectively compete with resident soil cations ( $Na^+$ ,  $K^+$ ,  $Ca^{2+}$ , and  $Mg^{+2}$ ) for exchange sites. Results from batch equilibrium tests of clay suspensions conducted by Beveridge and Pickering (1981) indicated that cationic surfactants were effective in desorption of all studied metals (lead, cadmium, copper, and zinc) from montmorillonite clays. One promising aspect of their study showing cationic surfactant removal of heavy metals from soils is the very low solution concentrations (0.005% by weight) needed to cause desorption. The concentrations that Beveridge and Pickering (1981) used were two orders of magnitude less than the surfactant concentrations proposed for application in environ-

mental remediation of nonaqueous phase liquids. Consequently, compared with organic contaminants, surfactants may be more cost effective in removal of heavy metals.

The objective of this research was to determine with batch equilibrium testing the ability of commercially available cationic surfactants to remove Pb from soils and to investigate the influence of pH on lead desorption. The results provide valuable information on the feasibility of using surfactants in environmental remediation of heavy metals and outline the direction for future research on this topic.

## MATERIALS

### Surfactants

Surfactants are organic compounds that on the molecular level are comprised of both hydrophobic and hydrophilic components. Because of this amphipathic structure, surfactant molecules in aqueous solution tend to concentrate at phase boundaries, thereby altering interfacial properties such as surface tension. At solution concentrations below what is referred to as the critical micelle concentration (CMC), surfactants exist as individual molecules or "monomers." Upon reaching the CMC, surfactant molecules begin to form aggregates called micelles, and the monomer concentration reaches

TABLE 2. Surfactant properties.

Surfactant	Molecular Weight	Active Ingredient (% by weight)	Surface Tension <sup>a</sup> (dynes/cm)	Viscosity <sup>a</sup> (mm <sup>2</sup> /sec)	pH <sup>a</sup>	Product Name
PMDAC-1	600	98	35.7	1.0014	6.53	Emcol CC-9
PMDAC-2	1600	98	33.0	1.2162	7.25	Emcol CC-36
PMDAC-3	2500	98	32.6	1.4387	7.31	Emcol CC-42
PDEP	3300	98	40.6	1.3379	6.45	Emcol CC-57
LC	399	97.5	32.0	1.0136	6.35	Emcol E607-L
DTAB	308.4	99	40.0	1.0025	7.12	-
DPC	283.9	98	32.1	0.9741	6.83	-
DB	414.5	96	33.6	1.0211	7.10	-
ISML	503	24.7	31.9	1.0516	4.16	Emcol ISML
TTAB	336.4	99	37.2	1.0033	6.76	-

<sup>a</sup>Temperature is 23.4°C; solution concentration,  $2.5 \times 10^{-2}$  mole/L; surface tension precision,  $\pm 0.5$  dynes/cm; viscosity precision,  $\pm 0.0005$  mm<sup>2</sup>/sec (Centistocke).

**TABLE 3.** Soil characteristics.

Soil Series	USDA Classification	Extractable Bases (meq/100 g)	Cation Exchange Capacity <sup>a</sup> (meq/100 g)	pH <sup>b</sup>	Specific Surface Area (m <sup>2</sup> /g)	Organic Carbon Content (weight %)
Teller	Loam 52% sand 31% silt 17% clay	Na <sup>+</sup> , 0.84 K <sup>+</sup> , 0.99 Ca <sup>+2</sup> , 6.28 Mg <sup>+2</sup> , 2.39	~14	6.2	16.2	1.2
Slaughterville	Sandy loam 55% sand 31% silt 14% clay	Na <sup>+</sup> , 0.22 K <sup>+</sup> , 0.26 Ca <sup>+2</sup> , 8.05 Mg <sup>+2</sup> , 1.62	~10	8.2	13.4	0.3

<sup>a</sup>Cation exchange capacity for Teller loam was calculated assuming a base saturation of 75%, which is average for Payne County, Oklahoma, soils in this pH range. With pH of 8.32, total extractable bases are assumed to be equal to the cation exchange capacity for the Slaughterville sandy loam.

<sup>b</sup>pH measured at 23°C.

a constant value. Surfactants are classified according to charge of the hydrophilic group as being anionic, cationic, amphoteric (positive and/or negative charge), or nonionic.

The 10 commercially available cationic surfactants used are listed in Table 1. Also included in this table are chemical formulas, manufacturing sources, product names, and abbreviations used to designate surfactants throughout the remainder of the text. All surfactants were obtained from the Aldrich Chemical Company or the Organic Division of WITCO Corporation. Table 2 provides surfactant molecular weight, the percentage of active ingredient, measured solution surface tension, solution pH, and solution viscosity. Surfactant solution properties in Table 2 were measured at a concentration of 0.025 mole/L. Surface tension values were measured with a Fisher Scientific Model 21 Tensiometer. Viscosities were obtained with a Canon Instrument Co. Size 50 viscometer.

## Soil

The two soils tested were Slaughterville sandy loam and Teller loam. Their properties are listed in Table 3. Both the Slaughterville sandy loam (Thermic Udic Haplustolls) and Teller loam (Thermic Udic Argiustolls) are typical top soils from the southern plains region and were collected from locations near Perkins, Oklahoma. Soil properties, with the exception of specific surface, were determined using standard procedures described in *Methods of soil analysis*, Parts 1 (ASA and SSSA, 1982) and 2 (ASA and SSSA, 1986). Specific surface area was calculated from nitrogen gas (N<sub>2</sub>) sorption isotherms (Brunauer et al., 1983). Properties of both soils are similar, except that Slaughterville was calcareous and Teller loam had a slightly higher organic carbon content. These fine-grained soils were chosen because their high sorption potential made them good candidates for evaluating the ability of cationic surfactants to displace Pb.

**TABLE 4.** Phase I: Surfactant concentration dependence on lead desorption (%Pb) from Slaughterville sandy loam.<sup>a</sup>

Surfactant	Surfactant Concentration (mole/L)									
	0.00625		0.0125		0.025		0.05		0.1	
	pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb
PMDAC-1	7.28	1.6	7.05	2.4	6.53	4.0	6.24	7.4	6.21	8.0
PMDAC-2	7.35	0.4	7.33	0.6	7.25	0.8	7.21	1.0	7.11	1.4
PMDAC-3	7.44	0.6	7.40	0.6	7.31	0.8	7.16	1.0	6.97	1.6
PDEP	6.69	3.0	6.57	3.6	6.45	4.0	6.35	4.6	6.3	5.2
LC	6.81	11.6	6.63	19.8	6.35	34.0	5.78	44.8	4.76	58.8
DTAB	7.40	1.2	7.37	1.6	7.12	2.6	6.92	4.4	6.76	4.8
DPC	7.47	1.6	7.32	3.2	6.83	24.0	6.26	40.0	5.14	50.0
DB	7.30	3.2	7.18	4.6	7.10	4.8	7.06	4.4	7.02	1.0
ISML	4.86	61.0	4.42	65.0	4.16	72.6	4.0	75.0	3.97	82.0
TTAB	7.03	1.6	6.86	2.4	6.74	3.8	6.59	4.8	6.46	5.4
EDTA	4.72	91.4	4.66	93.0	4.75	95.4	4.42	86.6	5.0	90.8

<sup>a</sup>For the background comparison test conducted with deionized water, the equilibrium pH was 8.3 and the Pb desorbed was 1%.

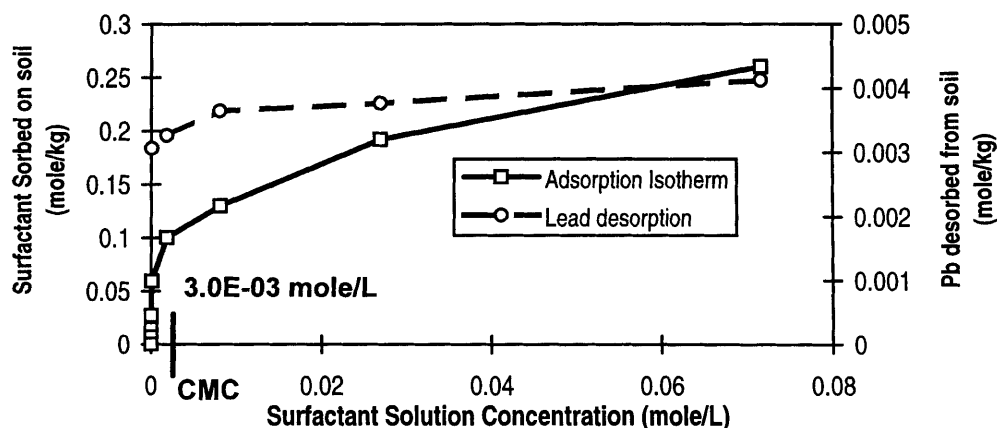


FIGURE 1: ISML adsorption isotherm with corresponding Pb desorption.

## EXPERIMENTAL PROCEDURES

The investigation was performed in two phases. First, Pb desorption effectiveness was explored with 10 surfactants at different concentrations using the Slaughterville sandy loam. Then, for the six most promising surfactants from the first phase, the pH influence on Pb desorption was investigated at a constant surfactant concentration of 0.025 mole/L. Phase II testing was done with Slaughterville and Teller soils.

### Soil Preparation

Soil was air dried, sieved through a number 20 sieve (0.850 mm), mixed for uniformity, and oven dried at 105°C for 24 hr to remove moisture. Heating the soil suppressed resident microorganisms that had the potential to biodegrade the surfactants.

### Phase I: Batch Equilibrium Tests: Different Surfactant Concentrations

Pb desorption from Slaughterville sandy loam was measured for each of 10 cationic surfactants by using batch equilibrium tests. Three grams of soil were placed in 125-mL flasks. To each flask, 2.5 g of an aqueous solution containing 0.0048 g of  $\text{Pb}(\text{NO}_3)_2$  was added, mixed with the soil,

and left for 3 hr to equilibrate. This gave an initial lead concentration with respect to dry soil of 1000 parts per million (ppm). Next, 60 g of surfactant solution was added to the flask. Five different surfactant solution concentrations were tested: 0.00625, 0.0125, 0.025, 0.05, and 0.1 mole/L. All samples were then placed in a shaker bath for 1 hr at 23.5°C, shaken at 200 revolutions per minute (rpm), and left for 24 hr to equilibrate. After this, 12 mL of solution were transferred to a 15-mL plastic centrifuge tube and centrifuged at 5000 rpm for 20 min to obtain a clear solution. An atomic absorption spectrophotometer (model 373; Perkin-Elmer) was used to measure Pb in solution ( $\lambda$ , 283.3 nm). For comparison, experiments were also conducted with both deionized water and ethylenediaminetetraacetic acid (EDTA) solutions as the Pb extractant. Surfactant effectiveness was quantified by comparing the mass of Pb initially sorbed onto the soil with the amount of Pb desorbed into solution.

The final part of Phase I focused on determination of adsorption isotherms for the three most effective surfactants. Batch equilibrium procedures similar to those just described were used to generate the surfactant adsorption isotherms. Surfactant solution concentrations after equilibrium were compared to those of the initial solution to determine the amount of surfactant sorbed onto soil particle surfaces. The

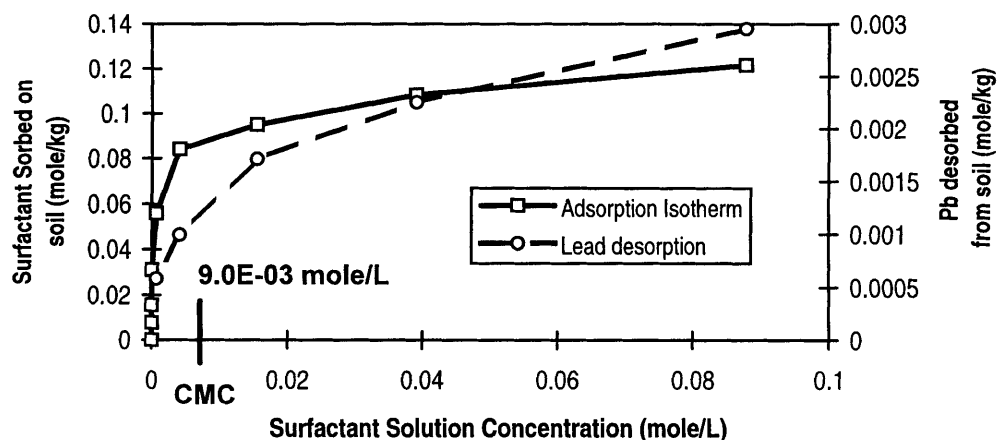


FIGURE 2: LC adsorption isotherm with corresponding Pb desorption.

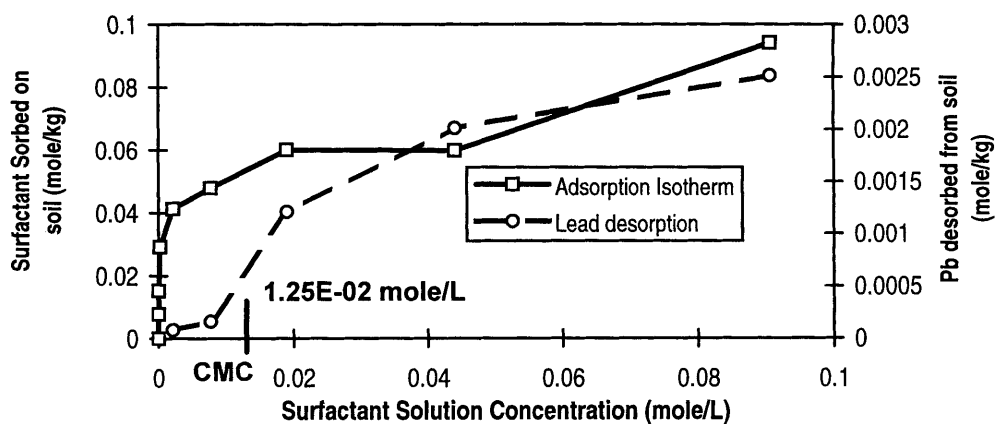


FIGURE 3: DPC adsorption isotherm with corresponding Pb desorption.

surfactant adsorption isotherms were then constructed by plotting the surfactant concentration sorbed onto soil versus the equilibrium surfactant solution concentration. Solution LC and DPC were analyzed by the Orange II method (Scott, 1968), and ISML was analyzed with a modified version of the Methyl Orange procedure (Simon et al., 1990). Absorbance measurements of the surfactant-dye complex in a chloroform solution were performed using a spectrophotometer (model 1100; Hitachi) at a length wave of 485 nm for LC and DPC and 418 nm for ISML.

#### Phase II: Batch Equilibrium Tests: pH Effect

Based on results from Phase I, the six most effective surfactants were tested to determine the impact of pH on surfactant-affected lead desorption. This experimental series involved six levels of pH adjustment from 4 to 9 and a fixed surfactant solution concentration of 0.025 mole/L. That solution concentration was chosen because it is comparable to concentrations used in other field and laboratory surfactant remediation. Nitric acid ( $\text{HNO}_3$ ) (1.0 mole/L) or sodium hydroxide (NaOH) (1.0 mole/L) was used to adjust the pH of the soil-surfactant-lead solution.

Batch samples were prepared by the same method as used for Phase I. Acid or base was then added to the soil-surfactant-lead solution, and the pH was adjusted to target values.

After 24 hr, the pH was readjusted if needed. Samples were analyzed for lead desorption in the same manner as Phase I. This testing allowed for determination of the relationship between pH and surfactant-affected Pb desorption from two fine-grained soils. For comparison, Pb desorption by EDTA and water was also determined.

## EXPERIMENTAL RESULTS

### Phase I

Results for all 10 surfactants and EDTA are presented in Table 4, which shows the relationship between Pb desorption and the concentration of the surfactant solution. Surfactants which caused the highest lead desorption were ISML, LC, and DPC. The pH conditions for the batch equilibrium tests are also provided in Table 4. For all surfactants except DB, an increase in the added surfactant solution concentration resulted in decreased pH and increased Pb desorption. Only 1% of the lead was desorbed by deionized water. The highest lead desorption occurred at a concentration of 0.1 mole/L: ISML (82%), LC (59%), and DPC (50%). The least effective surfactants—PMDAC-2, PMDAC-33, DB, and DTAB—were excluded from further study.

Surfactant adsorption isotherms for ISML, LC, and DPC are plotted along with Pb desorption curves in Figures 1–3. The highest surfactant adsorption and highest lead desorp-

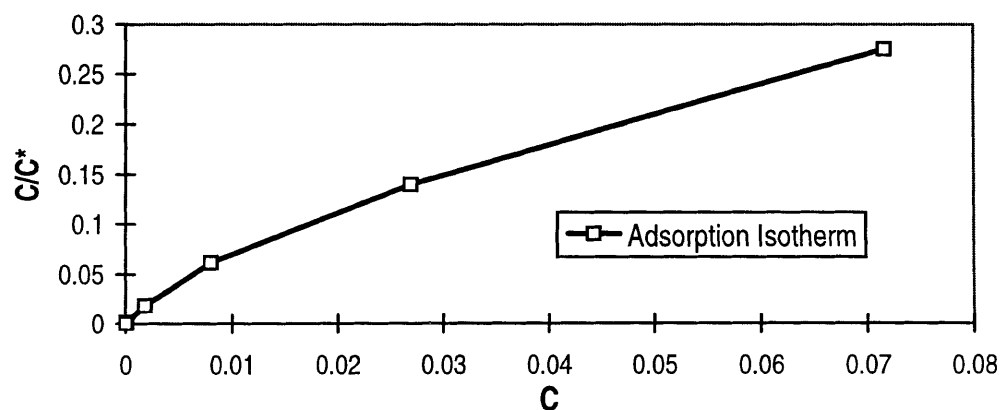


FIGURE 4: Langmuir isotherm fitting for ISML on Slaughterville.

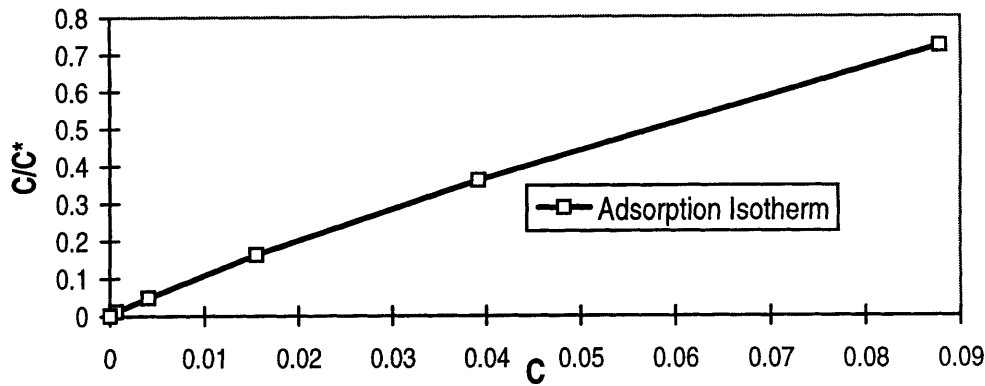


FIGURE 5: Langmuir isotherm fitting for LC on Slaughterville.

tion occurred with ISML. Figures 4–6 graph  $C/C^*$  versus  $C$ , which were used to determine if surfactant adsorption could be described by the Langmuir equation (Fetter, 1993).  $C$  is the equilibrium concentration in mole/L, and  $C^*$  is the sorbed surfactant concentration on soil in mole/kg.  $C/C^*$  versus  $C$  curves, which plot as a straight line, indicate Langmuir-type adsorption. LC exhibited behavior consistent with Langmuir adsorption, while ISML and DPC displayed only Langmuir adsorption at low concentrations.

### Phase II

The first phase of study showed increasing surfactant concentration to correspond with decreasing pH and increasing Pb desorption from the Slaughterville sandy loam. Reduction of pH often results in increased solubility and mobility of heavy metals within the soil environment. To separate out the effect due to pH reduction alone, a series of batch tests for six different cationic surfactants was conducted in which pH was varied between 4 and 9, while the surfactant concentration was kept constant at 0.025 mole/L. Phase II experiments included both Slaughterville and Teller soils to determine if soil type influences lead desorption. Data analysis involved comparing the results of the six surfactants to those of pH-adjusted water. For the same soil, increased amounts of Pb desorption for a surfactant test series over that of the pH-adjusted water series is evidence of overall sur-

factant effectiveness in removal of heavy metals. The pH effect on EDTA (0.025 mole/L) was also addressed during this part of the investigation.

Phase II test results are presented in Table 5 for the Slaughterville sandy loam and in Table 6 for the Teller loam. In comparison with pH-adjusted water, Tables 5 and 6 show ISML, LC, and DPC to be the most effective surfactants. Results for these three surfactants, EDTA, and pH-adjusted water are displayed in Figure 7 for the Slaughterville sandy loam and Figure 8 for the Teller loam. Slaughterville Pb desorption for ISML, LC, and DPC increased dramatically as pH was reduced from 7 to 4 (Figure 7). At a pH of 4, Slaughterville Pb desorption is 83, 78, and 68% for ISML, LC, and DPC, respectively. A comparison of Figures 7 and 8 shows surfactant-affected Pb desorption to be much less with the Teller than the Slaughterville. Figure 8 shows a substantial increase in Teller Pb desorption for all three surfactants as pH is lowered below a value of 5. At a pH of 4, Teller Pb desorption is 36, 32, and 29% for ISML, LC, and DPC, respectively. EDTA desorbed 94–97% of Pb and was not influenced by either pH or soil type.

### DISCUSSION ●

Cationic surfactant-enhanced Pb desorption results in part from soil ion exchange processes. Inorganic metal cations such as divalent lead are bound to negatively charged soil

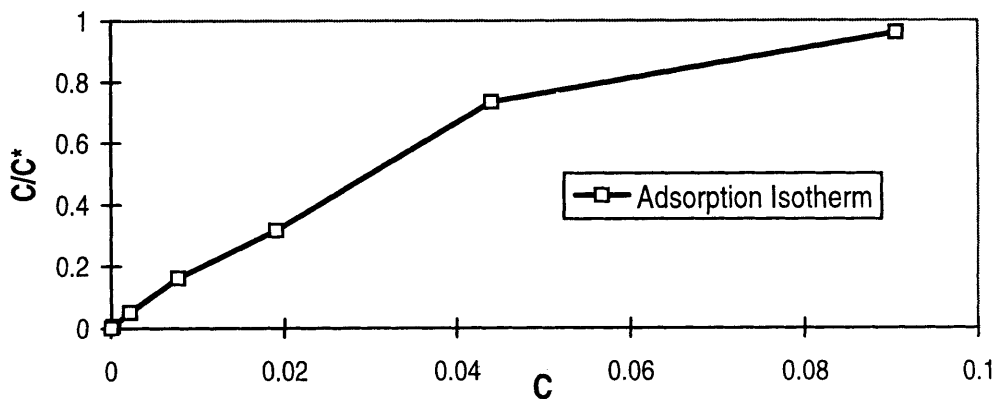


FIGURE 6: Langmuir isotherm fitting for DPC on Slaughterville.

**TABLE 5.** Phase II: pH effect on lead desorption (%Pb) from Slaughterville sandy loam.

Surfactant															
PMDAC-1		PDEP		TTAB		DPC		LC		ISML		EDTA		Water	
pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb
4.20	22.8	4.09	7.4	3.92	39.3	4.2	68.0	3.9	78.0	4.02	81.3	3.99	98.8	4.12	26.7
4.93	19.1	4.99	4.3	4.74	33.7	5.6	45.9	5.16	55.0	5.25	69.1	4.95	99.4	5.29	17.2
5.92	9.8	5.89	3.7	6.26	19.3	6.33	22.4	6.31	28.5	6.34	44.6	6.00	98.7	6.01	8.7
6.15	6.3	6.97	3.3	6.99	4.3	7.6	1.5	6.85	12.8	6.98	22.0	7.06	97.6	7.11	4.1
7.30	1.3	8.01	3.0	7.40	2.0	8.3	1.1	7.45	5.4	8.15	7.8	7.99	98.2	8.21	2.2
8.30	0.7	9.19	1.3	8.06	1.5	8.55	0.9	8.72	3.0	8.91	3.0	8.47	95.4	8.69	1.7

surfaces. When a large cation such as a cationic surfactant is introduced into the soil environment, it competes with metal cations at surface exchange sites. Due to London–van der Waals attraction forces, which typically increase with molecular weight, the larger surfactant cations have a distinct competitive edge over the smaller metal cations with respect to electrostatic adsorption (Rosen, 1989).

Soil pH also influences metal solubility and mobility in the subsurface. Heavy metal solubility and mobility are inversely related to soil pH. Liang and McCarthy (1995) reported that for silica at pH below 4.2, essentially all of the lead remains in solution (Pb II). As pH increases from 4.2 to 7, there is a sharp decrease of Pb in solution. At pH >7, lead is preferentially sorbed on soil and appears only in insoluble Pb complexes. Surfactant solutions with pH <6 were effective in desorbing Pb from soil, but surfactants with pH >6 were not effective, as shown in Figure 9. At surfactant concentration of 0.1 mole/L, lead desorption from contaminated soil was inversely proportional to the surfactant's pH. According to Pierzynski et al. (1994), lead at pH <6 predominates as the Pb<sup>2+</sup> form, while at pH >6 the Pb-hydroxy complexes predominate. Lead hydroxide complexes, PbOH<sup>+</sup>, form strong bonds with Fe and Mg oxides in soil. However, Pb<sup>2+</sup> is only weakly adsorbed by electrostatic bonding (Kiniburgh and Jackson, 1981; Basta and Tabatabai, 1992). This suggests that the surfactants used are only effective in mobilizing electrostatically bonded Pb<sup>2+</sup>.

Two processes may occur simultaneously when surfactants with low pH are added to Pb-contaminated soil: first,

pH is lowered by adsorption of H<sup>+</sup> and by desorption of Pb<sup>2+</sup> due to increasing Pb solubility; second, desorption of Pb from exchange sites is further enhanced by adsorption of surfactant cations, which is thermodynamically favored due to London–Van der Waals forces (McBride, 1994). These processes account for the increased effectiveness in Pb removal from the Slaughterville at high concentrations (0.1 mole/L) of ISML, LC, and DPC over the other cationic surfactants. The 0.1 mole/L solution pH values for ISML, LC, and DPC are 3.97, 4.76, and 5.14, respectively. The seven other cationic surfactants at 0.1 mole/L concentrations have higher pH values which range between 6.21 and 7.11. Low pH alone, however, does not account for the effectiveness of ISML, LC, and DPC. At similar pH values, ISML, LC, and DPC remove more Pb from the Slaughterville and Teller soils than does aqueous solution at the same pH (Figures 7 and 8). Consequently, preferential electrostatic adsorption at exchange sites due to London–van der Waals attractions is important for these three surfactants. Surfactant molecular structure may play an important role in lead desorption. ISML, LC, and DPC have a positively charged nitrogen ion inside the ring structure, which distinguishes them from the rest of the tested surfactants. Lead desorption is not a function of a surfactant molecular weight, as shown in Figure 10. Over the range of molecular weights tested, molecular size does not affect adsorption to mineral surfaces.

An important factor affecting the metal adsorption is soil organic matter content. An increase in fulvic acid in soil increases Pb sorption due to formation of Pb–fulvic acid com-

**TABLE 6.** Phase II: pH effect on lead desorption (%Pb) from Teller loam.

Surfactant															
PMDAC-1		PDEP		TTAB		DPC		LC		ISML		EDTA		Water	
pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb	pH	%Pb
4.23	2.8	3.91	5.4	4.14	16.5	3.99	29.6	3.50	43.7	3.88	35.4	4.18	94.4	4.02	3.3
4.98	2.0	4.85	3.7	5.24	2.6	4.49	10.4	3.92	31.5	4.77	13.7	5.01	94.4	5.00	1.1
5.98	1.7	5.97	3.0	6.14	0.8	5.19	3.9	4.50	20.0	5.30	6.4	5.97	95.0	6.01	0.7
6.96	1.7	6.97	2.8	6.75	0.5	6.17	1.1	5.51	3.9	6.02	3.3	7.14	95.0	6.93	0.5
7.89	1.6	8.05	2.8	7.38	0.4	7.17	0.4	7.02	1.5	7.13	2.0	8.18	93.2	7.96	0.4
8.38	1.5	8.58	2.6	7.52	0.2	7.98	0.2	7.92	1.3	8.71	1.5	8.68	94.3	8.26	0.4

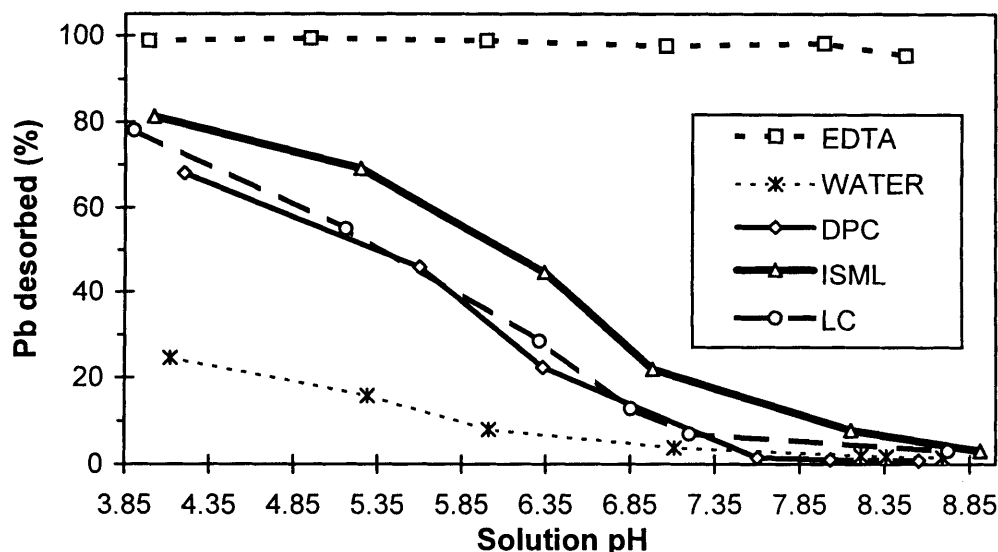


FIGURE 7: Lead desorption with pH change from Slaughterterville sandy loam.

plexes with strong chemical bonds (Logan and Traina, 1993). This is probably the reason why desorption of Pb from the Teller loam (1.2% of organic carbon content) is lower than from the Slaughterterville loam (0.3% of organic carbon content). Also, a higher percentage of clay, larger surface area, and higher cation exchange capacity associated with Teller loam influences lower Pb desorption from Teller soil.

ISML, LC, and DPC adsorption and corresponding Pb desorption occur at surfactant equilibrium concentration above the CMC (Figures 1–3). This suggests that adsorption for these three surfactants dominates over critical micelle formation (CMC), and this is consistent for both the Slaughterterville and Teller soils.

Pb desorption by surfactants was compared with desorption by EDTA, a complexing agent having a high affinity for divalent metal cations. EDTA removed between 94 and 97% of soil Pb across the entire pH range studied for both

soils. At 0.1 mole/L, the most efficient surfactant was ISML, which desorbed 82% Pb from the Slaughterterville soil. The high efficiency may be due to the presence of the lactic acid anion in ISML, which chelates soil Pb similar to EDTA. Cationic surfactants may be a better alternative than EDTA for soil remediation since they are cheaper and biodegradable. Further saturated column experiments with ISML and LC are needed to determine soil remediation efficiency. From the standpoint of economics, EDTA is ~2.5 times more expensive than ISML (Aldrich Chemical Co. and WITCO, personal communication). Cationic surfactants such as quaternary ammonium salts and fatty amines salts are readily biodegradable and will not accumulate in most ecosystems (Van Ginkel, 1995). EDTA is resistant to biodegradation and commonly found in the environment due to widespread industrial, pharmaceutical, and agricultural use (Hering, 1995). Consequently, EDTA is often

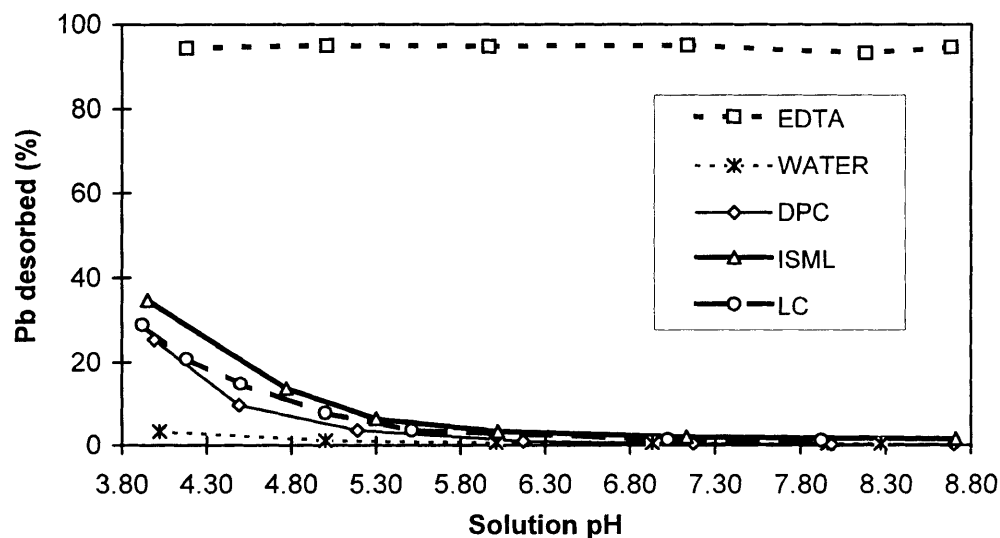


FIGURE 8: Lead desorption with pH change from Teller loam.



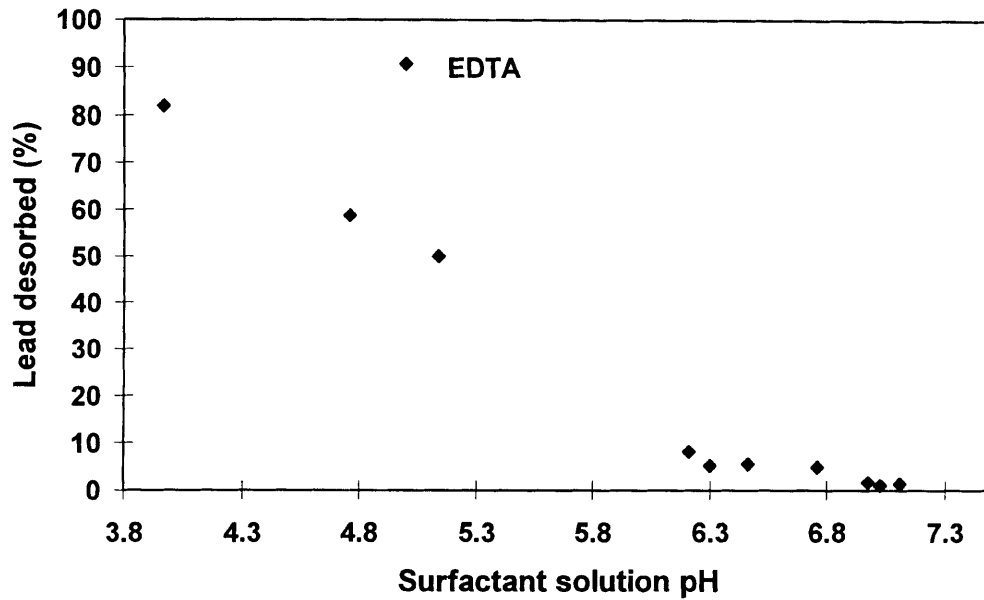


FIGURE 9: Lead desorption from Slaughterville as a function of solution pH for 10 surfactants at 0.1 mole/L.

found to be present in groundwater, sewage effluent, fresh-water, and even drinking water.

**SUMMARY AND CONCLUSION**

This study focused on the feasibility of using cationic surfactants to remove Pb from soil. The experimental methods developed can be easily applied to research on other heavy metals. In Phase I, lead desorption from soil was measured as a function of surfactant concentration (0.00625–0.1 mole/L). Three of 10 cationic surfactants screened (ISML, LC, and DPC) were far more effective in desorbing Pb from soils. At an initial surfactant solution concentration of 0.1 mole/L, ISML, LC, and DPC desorbed 82, 59, and 50%, respectively, of Pb present in the Slaughterville sandy loam. The most efficient surfactant was ISML, which is superior to the

other due to its low pH and its lactate acid group. Deionized water alone could desorb only 1%.

Phase II investigated the relationship of pH on surfactant-affected desorption of Pb from both Teller loam and Slaughterville sandy loam. Pb desorption was pH dependent, that is, with decreasing pH, there was increasing Pb desorption. At a pH of 4 and a concentration at 0.025 mole/L, the best three cationic surfactants, ISML, LC, DPC, desorbed 83, 78, and 68% Pb, respectively, from the Slaughterville sandy loam along with 36, 32, and 29%, respectively, from the Teller loam. Phase II results show that cationic surfactants combined with pH adjustment can effectively remove Pb from soil. Based on results from our investigation, cationic surfactant utilization could potentially provide an alternative for in situ cleanup of heavy metals from soil.

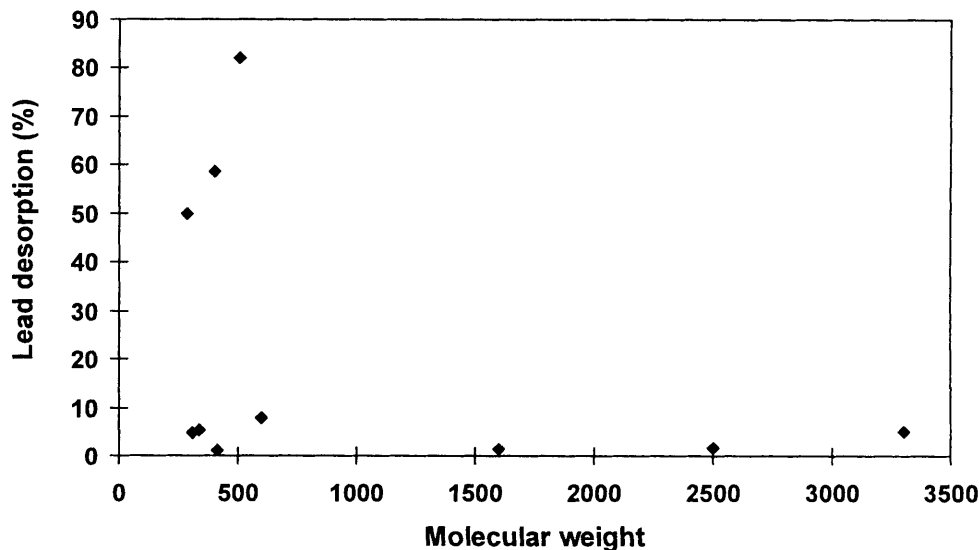


FIGURE 10: Lead desorption from Slaughterville as a function of molecular weight for 10 surfactants at 0.1 mole/L.

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