

Saturated Column Feasibility Study Using Cationic Surfactants for In Situ Removal of Lead from Soil

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ABSTRACT

This investigation determined the in situ cleanup potential for using cationic surfactants to remove lead from soil under saturated conditions. To accomplish this task, flushing tests were conducted on saturated columns containing a sandy loam soil spiked with 1000 ppm of lead. Four different flushing treatments were investigated: water, dilute nitric acid (pH 3.6), and two cationic surfactant solutions above the critical micelle concentration—0.025 mol/L lapyrium chloride (LC), and 0.025 mol/L isostearamidopropyl morpholine lactate (ISML). These two surfactants were chosen based on previous batch equilibrium tests. In the saturated column experiments conducted in this study, ISML and LC desorbed 94 and 92% of the lead from the Slaughtererville soil, respectively, while water and dilute nitric acid accounted for only 1.5 and 1.7%, respectively. Sorption processes substantially reduced the mobility of both surfactants as evidenced by retardation factors of 21 for ISML and 18 for LC. Twenty pore volumes of 0.025 mol/L ISML were required to remove 50% of the lead as compared with 230 pore volumes of 0.025 mol/L LC, indicating that ISML was substantially more efficient than was LC. Based on these findings, ISML appears to show good potential for in situ use in cleanup of lead from soil.

Key Words: cation exchange, cationic surfactant, heavy metal contamination, lead desorption, saturated flow.

INTRODUCTION

Soil contamination by lead is one of the most common problems found at landfills and hazardous waste sites across the country. Because of its toxicity, excess levels of lead present in the environment pose substantial health risk concerns. Soil containing high levels of lead are a potential source of further contamination of surface water through runoff and groundwater by leaching. Wind erosion also may spread surface contamination to adjacent areas. At the present time, there are no economically effective and efficient in situ methods for removing heavy metals from soil. Excavation and transport of heavy metal-contaminated soil to landfills has

been the standard method of soil remediation. Off-site transport and disposal of the contaminated soil involve high expense, liability, and appropriate governmental regulatory approval. Furthermore, recent United States Environmental Protection Agency (EPA) policy requires pretreatment before disposal in a landfill (Peters and Shem, 1995).

Several saturated column soil flushing studies have been conducted using the chelating agent EDTA to remove heavy metals. According to Reed et al. (1996), EDTA was effective in removing nearly 100% of the lead originally present. Peters and Shem (1995) found that EDTA removed 71% of lead from a soil with high clay content. The EPA (1997) reported that a 0.01 mol/L EDTA solution flushed 93% of lead (initial concentration 500 to 600 mg/kg) from a sandy loam. Despite the high percentage of lead removal by EDTA, there are questions regarding cost effectiveness (EPA, 1997) and a concern that EDTA is not biodegradable and would accumulate in ecosystems (Hering, 1995). The EPA determined that the greatest need for new remedial technologies in the Superfund Program is for heavy metals in soil (EPA, 1993), because existing remediation technologies are considered too costly and often do not work. Those that have been tried, such as pump and treat, vitrification, and electroosmosis, are either ineffective or extremely expensive (Peters and Shem, 1995). However, because very few techniques exist for in situ remediation of soils contaminated with heavy metals, there is an increased interest in new technologies to treat in situ contaminated soils in place.

In recent years, the potential use of biodegradable surfactants in environmental remediation has gained significant attention. 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 by Sale and Pitts (1989), Abdul et al. (1992), and Abdul and Ang (1994) indicate the effectiveness and efficiency of using surfactants to flush organic contaminants from both saturated and unsaturated sediments under typical field conditions. The effect of surfactants on hydraulic properties of both saturated and unsaturated soils has been investigated by Allred and Brown (1995).

Although very little research has been conducted on this topic, surfactants also have the potential for environmental

TABLE 1. Surfactants used and their properties.

Surfactant Name, Abbreviation, Source, and Molecular Formula	Molecular Weight	Active Ingredient % (by Weight)	Surface Tension ^a (dynes/cm)	Kinematic Viscosity ^a (mm ² /sec)	pH ^a	Product Name
Lapyrium chloride (LC) WITCO	399	97.5	32.0	1.0136	6.35	Emcol E607-L
[C ₁₁ H ₂₃ C ₃ O ₂ H ₅ NC ₂ ONC ₅ H ₅]Cl Isostearamidopropyl morpholine Lactate (ISML) WITCO	503	24.7	31.9	1.0516	4.16	Emcol ISML
C ₂₅ H ₅₀ N ₂ O ₂ *C ₃ H ₆ O ₃						

^aTemperature = 23.4°C; solution concentration = 2.5×10^{-2} mol/L; surface tension precision = ± 0.5 dynes/cm; viscosity precision = ± 0.0005 mm²/sec (Centistocke).

remediation of heavy metals. Cationic surfactants can be used to modify surfaces of soil to promote displacement of metal cations to the liquid phase. Low concentrations of cationic surfactant cause the transfer of the soil-bound metal to the liquid phase through ion exchange. Bouchard et al. (1988) determined that a cationic surfactant could compete effectively with resident soil cations (Na⁺, K⁺, Ca²⁺, and Mg²⁺) for exchange sites. Results from batch equilibrium tests of clay suspensions conducted by Beveridge and Pickering (1981) indicated that cationic surfactants were effective in the desorption of copper, lead, cadmium, and zinc from montmorillonite clays.

Metal mobility is dependent on its solubility in aqueous solution and is controlled by pH. Cationic surfactants can influence soil pH and cause desorption of heavy metals into soil solution. Consequently, they offer the potential to be effective extractants of heavy metals from contaminated soils. Batch experiments with cationic surfactants and lead-contaminated soils by Kornecki et al. (1998) indicate that low pH aqueous cationic surfactants solutions can desorb up to 85% of lead from a calcareous sandy loam soil.

If cationic surfactants are proven effective in removing metals, one exciting possibility for these surfactants involves potential use in soil cleanup at sites containing mixed wastes. A flushing agent capable of removing both heavy metal and organic contaminants would provide a tremendous boost to the field of environmental remediation. Consequently, as a first

step, the focus of this research was to determine the in situ ability of cationic surfactants to desorb lead from a calcareous soil. This was accomplished with saturated column tests in which four different flushing treatments were investigated: water, dilute nitric acid, and two cationic surfactant solutions.

MATERIALS

Two cationic surfactant, lapyrium chloride (LC) and isostearamidopropyl morpholine lactate (ISML), which exhibited the highest lead desorption potential in the batch experiment (Kornecki et al., 1998), were chosen for this study. These surfactants were obtained from WITCO Chemical Corporation (Houston, Texas). Table 1 provides surfactant chemical formulas, along with some of their properties. Slaughterville soil was obtained from a location near Perkins, Oklahoma and used throughout these tests. Properties of Slaughterville sandy loam are listed in Table 2. The Slaughterville is calcareous soil and is classified as coarse-loamy, mixed, thermic Udic Haplustolls, a typical top soil from the southern plains region. Soil properties, with the exception of specific surface, were determined using standard procedures described in Methods of Soil Analysis, Part 1 and 2 (American Society of Agronomy and Soil Science of America, 1982, 1986). Specific surface area was calculated from nitrogen gas (N₂) sorption isotherms (Brunauer et al., 1983). Lead nitrate [Pb(NO₃)₂] with a purity of 99.5% was used in the preparation of spiked soil samples.

TABLE 2. Soil characteristics.

Soil Series	U.S. Department of Agriculture Classification	Extractable Bases (meq/100 g)	Cation Exchange Capacity ^a (meq/100 g)	pH ^b	Specific Surface Area (m ² /g)	Organic Carbon Content (weight %)
Slaughterville	Sandy Loam: 55% sand 31% silt 14% clay	Na ⁺ = 0.22 K ⁺ = 0.26 Ca ²⁺ = 8.05 Mg ²⁺ = 1.62	~10	8.2	13.4	0.3

^aCation exchange capacity (CEC) for the Slaughterville sandy loam with pH of 8.32, assumed to be equal to the total extractable bases.

^bpH measured at 23°C.

EXPERIMENTAL PROCEDURES

Soil Sample Preparation

Four saturated column experiments were conducted with spiked Slaughterville soil containing 1000 ppm of lead. The combination of lead and Slaughterville sandy loam were chosen simply because it represents one of the most undesirable conditions with respect to cleanup of heavy metals from soil. Lead is one of the least mobile of heavy metals in soil and is soluble only in settings where $\text{pH} < 5.0$ exists. The Slaughterville sandy loam has a relative large specific area, high cation exchange capacity, and a pH of 8.2. Consequently, lead can be expected to be fairly immobile in the Slaughterville soil.

The soil was air dried and sieved through number 20 mesh (0.85 mm), then oven dried at 110°C for 24 hr to remove moisture and suppress microbial activity. Next, 1996.8 g of soil were transferred to a plastic desiccator and 3.213 g of $\text{Pb}(\text{NO}_3)_2$ was added along with 600 mL of water. The saturated soil-lead mixture was then mixed by hand for 20 min using a plastic spatula to distribute the lead evenly. The soil was left covered for 4 hr to equilibrate. Next, the desiccator was left open for ~ 2 weeks to evaporate the water completely. Following this, the surface crust was broken up, and the sealed desiccator was mounted on a rotating shaft for 24 hr at 30 rpm to remix the sample.

Surfactant Solution Preparation

For two of the tests, the column was flushed with 0.025 mol/L cationic surfactant solutions. The concentration of 0.025 mol/L was similar to surfactant concentrations used in field remediation studies focusing on organic contaminant removal (American Petroleum Institute, 1985; Abdul et al., 1992). This concentration is above critical micelle concentration for both surfactants which is 0.003 and 0.009 mol/L for ISML and LC, respectively. For comparison purposes, two

additional column experiments were conducted, one with deionized water and the second with dilute nitric acid at pH 3.6. A pH of 3.6 was similar to that of the effluent obtained from flushing with the two cationic surfactants. The dilute nitric acid column test separated out the effect on lead desorption due to pH alone. Surfactant flushing solutions were prepared by adding deionized water to either LC or ISML. The surfactant solution concentration in all cases was 0.025 mol/L.

Columns

Column end plates and barrels were constructed from clear acrylic with inside dimensions of 39.6-mm diameter and 71.4-mm length. Packing proceeded in 10-mm lifts by using a steel rod to achieve a dry bulk density of 1.78 kg/L. That density corresponds to a porosity of 33%. The columns were vacuum saturated with distilled water to remove any entrapped air and then set up as shown in Figure 1. Tygon tubing with 0.762-mm internal diameter was used in conjunction with a peristaltic pump to maintain a 0.5 mL/min flow through the column. Flow was initiated and calibrated with distilled water. Three-way valves allowed rapid switching to the flushing solution once a uniform flow rate was established. Effluent was collected in either an automated fraction collector or a large flask, depending on the sample volume desired.

Sample Analysis

Effluent was analyzed for lead, pH , and surfactant concentration in test runs with ISML or LC. The collected effluent was centrifuged for 20 min at 5000 rpm to obtain a clear liquid. Filtering was not used because surfactants would have a strong tendency to concentrate on filter surfaces. During periods in which surfactant concentrations in the effluent were rapidly changing, every sample collected was analyzed. Otherwise, one in 10 samples were analyzed for surfactant concentration.

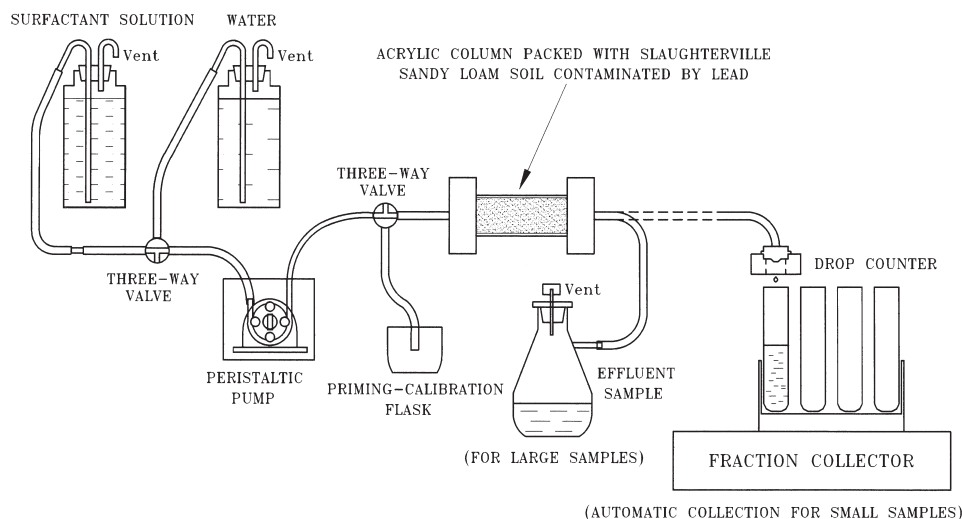


FIGURE 1. Schematic of column experimental set up.

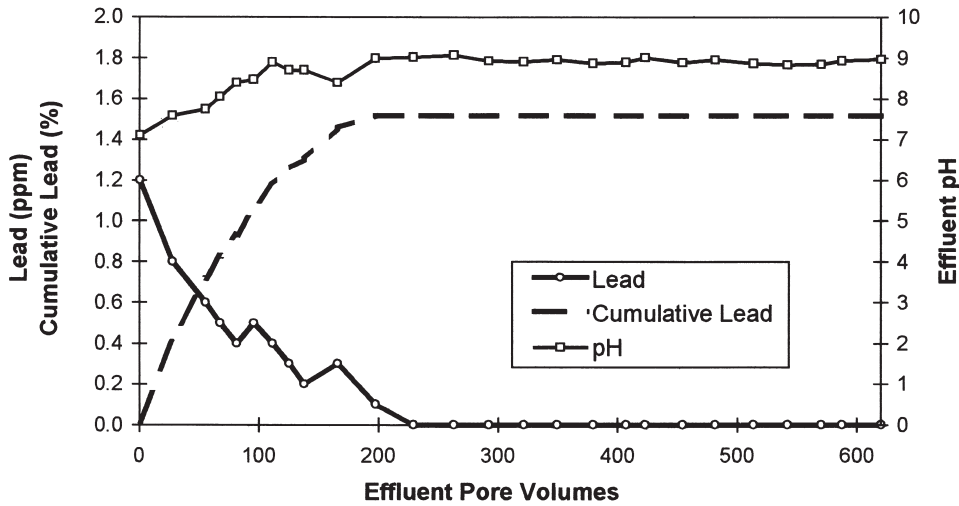


FIGURE 2. Water flush: Effluent pH, effluent lead concentration, and cumulative lead.

Lead content in each sample was determined using a Perkin-Elmer 373 atomic adsorption spectrophotometer. Surfactant concentration in the effluent was analyzed by two colorimetric methods. For LC, the Orange II method was used as described in Scott (1968). For ISML, a Methyl Orange method was adopted and modified from procedures described by Simon et al. (1990). Colorimetric measurements were done using a Hitachi (Tokyo, Japan) 1100 spectrophotometer at a wave length of 485 nm for LC and 418 nm for ISML.

RESULTS ●

Water Flush

Water produced only 1.5% lead desorption from Slaughterville soil. Lead desorption and effluent pH are shown in Figure 2. The maximum effluent lead concentration was only 1.2 ppm at 0.8 pore volume. A small concentration of lead in the effluent was observed up to 200 pore volumes, after which lead was not detected. The pH of the effluent increased from 7 to 9 between 1 to 200 pore volumes and then

remained constant to the end of experiment. Overall, water was ineffective in lead removal from the Slaughterville soil.

Nitric Acid Flush

Lead breakthrough and effluent pH with nitric acid (HNO₃) are presented in Figure 3. Throughout this experiment, nitric acid did not cause significant removal of lead from the soil column. The maximum effluent lead concentration was only 1.3 ppm at 2.8 pore volumes. After 260 pore volumes, lead was not detected in the effluent. The total amount of lead removed was only 1.7%. Effluent pH did not change substantially during the entire experiment of 430 pore volumes and remained between 7.9 and 8.9.

Emcol E-607L (LC)

Figure 4 shows the lead breakthrough and effluent pH for flushing with LC. Effluent pH decreased steadily during the entire experiment from pH 8 to the value of the injected solution pH 3.7. The maximum lead effluent concentration

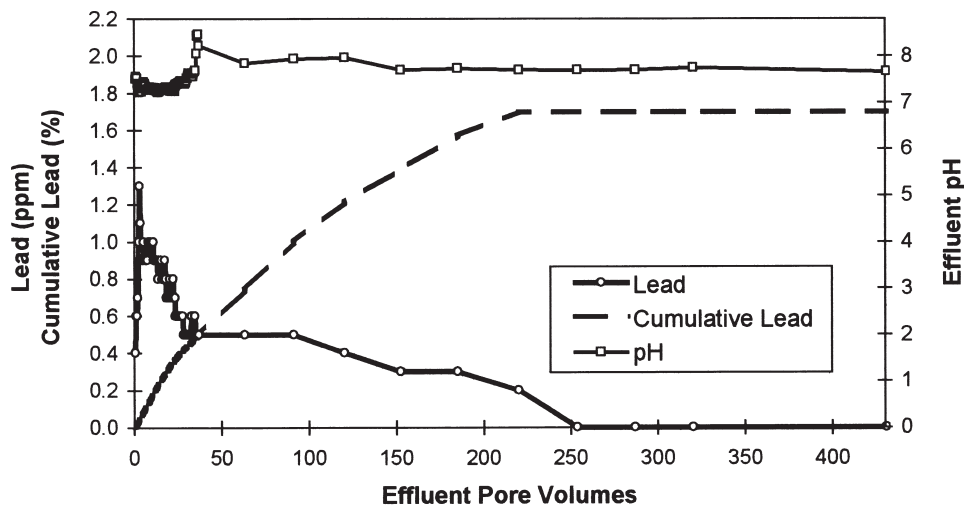


FIGURE 3. Nitric acid flush: Effluent pH, effluent lead concentration, and cumulative lead.

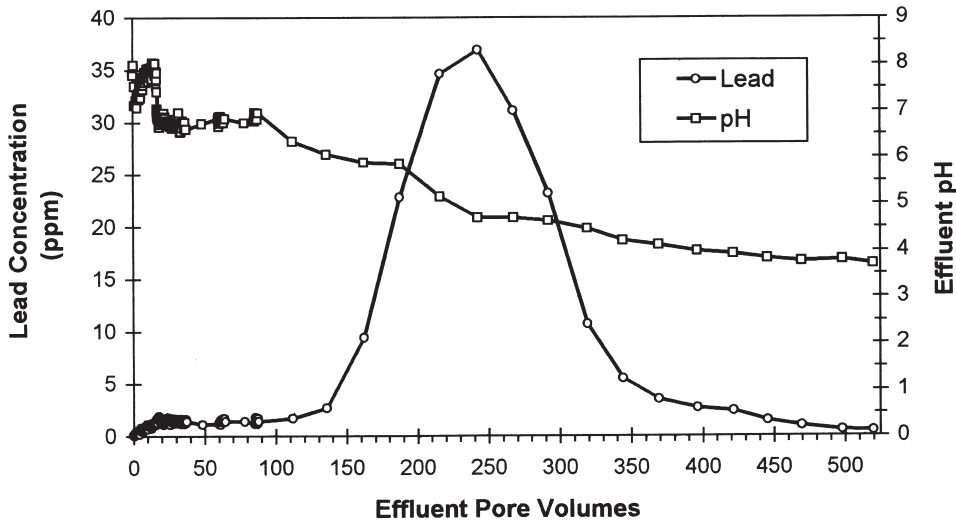


FIGURE 4. LC flush: Effluent pH and effluent lead concentration.

was 36.9 ppm at 243 pore volumes. Most lead was removed between 150 and 350 pore volumes as effluent pH dropped from 6 to 4. Figure 5 shows surfactant relative concentration (C/C_0), and effluent lead. The surfactant $C/C_0 = 0.5$ was reached at 17.7 pore volumes with 0.27% of lead removed and no significant lead concentration in the effluent. The maximum amount of lead in solution was observed when the surfactant C/C_0 reached 100%. Figure 6 shows a cumulative lead removal and relative surfactant concentration as a function of effluent pore volumes and pH. At a surfactant concentration of $C/C_0 = 0.5$, LC had removed only 3.5% of the lead. The total amount of lead removed from the column by LC was 92% at 520 pore volumes.

Emcol ISML

Figure 7 shows the lead breakthrough and effluent pH for flushing with ISML. Effluent pH decreased rapidly for 20 pore volumes from 7.9 and then leveled off at a value of the

injected solution pH 3.6. Figure 8 shows lead and surfactant breakthrough curves. From Figure 8, the retardation factor for ISML can be estimated as 21.5. The maximum effluent lead concentration was 346 mg/L at 20 pore volumes. Significant lead desorption with ISML was observed between 9 and 74 pore volumes when 70% of the lead was removed. Figure 9 shows cumulative lead removal, surfactant concentration (C/C_0), and effluent pH. At a surfactant concentration of $C/C_0 = 0.5$, ISML had removed 35.3% of the lead. Overall, ISML produced 94% lead desorption after 582 pore volumes.

DISCUSSION ●

Soil pH has a direct effect on metal solubility and mobility in the subsurface. In low soil pH environments, most metal-containing minerals become less stable, and mineral and organic matter functional groups protonate and induce metal desorption (Logan and Traina, 1993). Aqueous cat-

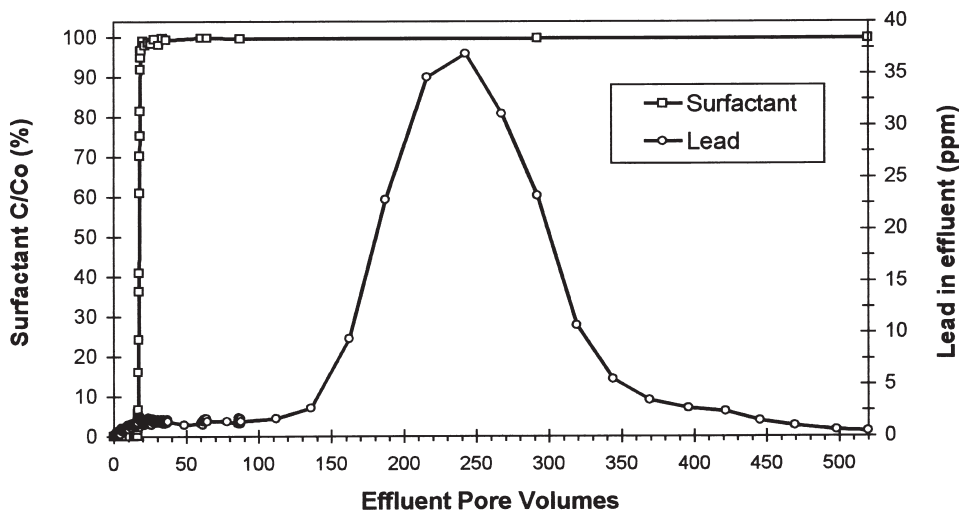


FIGURE 5. LC flush: Surfactant and lead breakthrough curves.

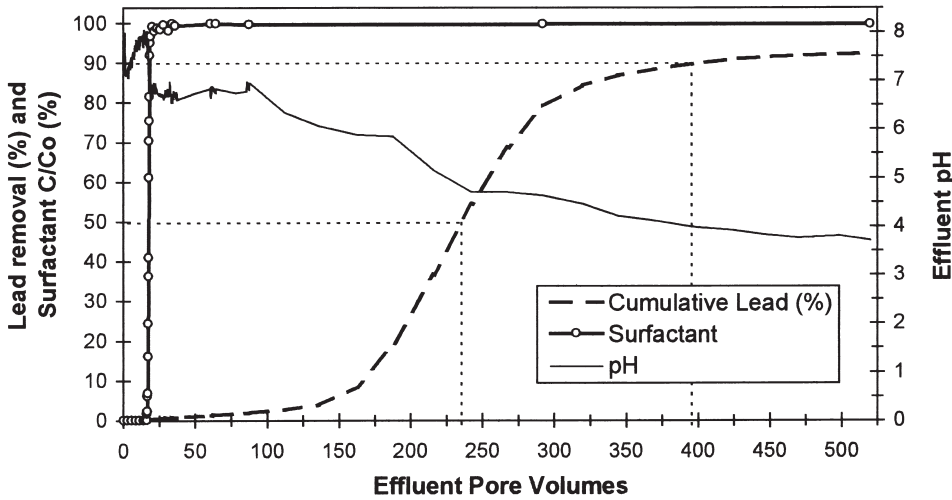


FIGURE 6. Cumulative effluent lead, effluent pH, and LC breakthrough curve.

ionic surfactant solutions (2.5×10^{-2} mol/L) having low pH, such as ISML (pH 3.6) and LC (pH 3.7), cause a decrease in soil pH which enhances the mobility of lead. In this case, two processes are observed simultaneously: (1) increased lead mobility due to lowering pH, and (2) competition for cation exchange capacity (CEC) sites due to ion exchange and London-van der Waals dispersion forces.

In all cases, change of pH was not rapid due to the large pH buffer capacity for Slaughterville soil. However, ISML lowered pH much faster than did LC. Diluted nitric acid with a pH of 3.5 (3.2×10^{-4} mol/L) has the same H^+ activity as cationic surfactant solution with a pH of 3.5. A saturated test with diluted nitric acid did not show any significant amount of lead desorption from soil. The dilute nitric acid did not reduce the soil pH value to the level which would increase lead solubility. Throughout the experiment, soil pH remained high (pH > 7) due to the high soil pH buffer capacity. This pH was above the adsorption edge (pH =

3.5) for lead. Slaughterville is a calcareous soil containing calcium carbonate; therefore, H^+ was neutralized by calcium carbonate and/or reabsorbed by soil. In contrast to diluted nitric acid, surfactants having the same solution pH caused significant lead desorption. This can be explained in part by the capability of large cations to compete with smaller inorganic cation such as lead for soil CEC sites.

In an effort to determine why ISML was more effective than was LC, the acidity of the two surfactants and nitric acid were measured by a standard titration method using 0.01 mol/L NaOH and color change of phenolphthalein indicator (American Public Health Association, American Water Works Association, & Water Pollution Control Federation, 1992). Acidity for ISML, LC, and nitric acid were 153.0, 6.2, and 3.5 mL, respectively. These values and pH response during flushing indicate that ISML was most effective due to its high acidity. The high acidity for ISML may be due to the presence of the lactic acid anion in ISML.

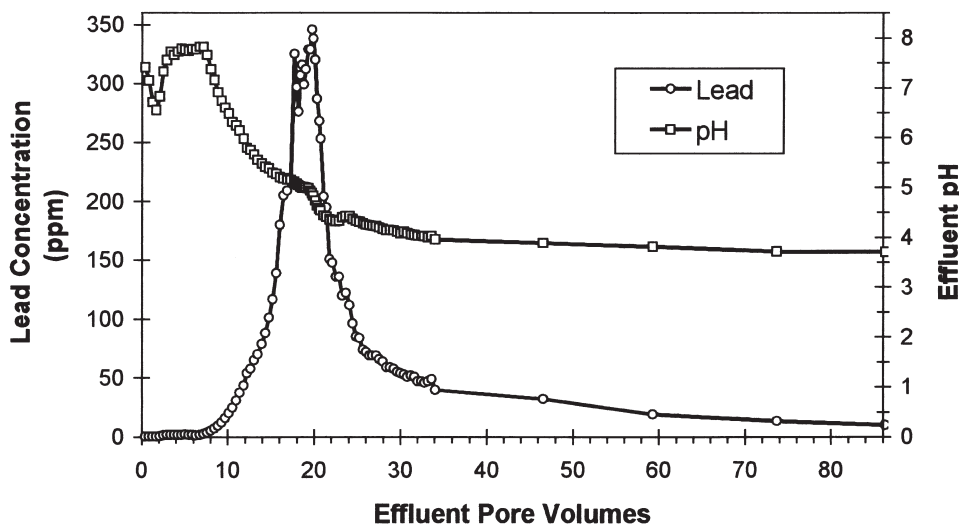


FIGURE 7. ISML flush: Effluent pH and effluent lead concentration.

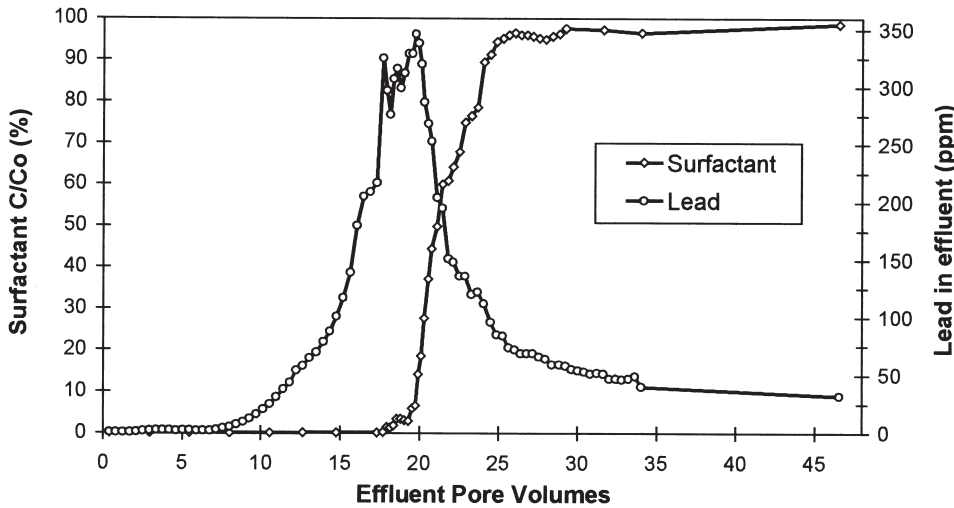


FIGURE 8. ISML flush: Surfactant and lead breakthrough curves.

However, LC was much more effective in lead removal than was nitric acid, considering that their acidities were similar. This would indicate that the surfactants have a reserve acidity not measured by simple titration.

The shape of the effluent curves for LC and ISML during breakthrough are almost vertical. This sharp, step-like breakthrough curve indicates low dispersion and strong surfactant adsorption. From 0 to 16 pore volumes (LC) and from 0 to 17.5 pore volumes (ISML), there is no surfactant present in the effluent. This is because the surfactant is completely sorbed into soil as it enters the column. As surfactant flows through the column, it outcompetes lead for soil exchange sites due to stronger Van der Waals attractions.

Experimental breakthrough curves for LC and ISML were fitted to theoretical breakthrough curves to estimate longitudinal dispersivity coefficient (D_L), and retardation factor for surfactant flow through the column (R_f). The computer program COLUMN version 1.4 (Brown et al., 1997) was used to

estimate these parameters. The soil properties such as bulk density and porosity were used to estimate dispersivity; flux flow, time of experiment, and relative surfactant concentration were used to estimate the retardation factor. Figures 10 and 11 show measured and fitted breakthrough curves for LC and ISML, respectively. Estimated model value of D_L were $1.21E-05$ cm²/sec (LC) and $4.97E-05$ cm²/sec (ISML). Fitted LC retardation was 17.8, and ISML retardation was 21.7.

The mass of surfactant adsorbed can be compared to the CEC in the soil. From basic principles, the equilibrium mass of sorbed solute may be computed from the solute concentration as

$$C^* = k_d C \quad (1)$$

where C^* is the adsorbed mass per mass of solid; C is the linear adsorption coefficient, and C is the solute concentration. The adsorption coefficient is related to the solute retardation, R , by

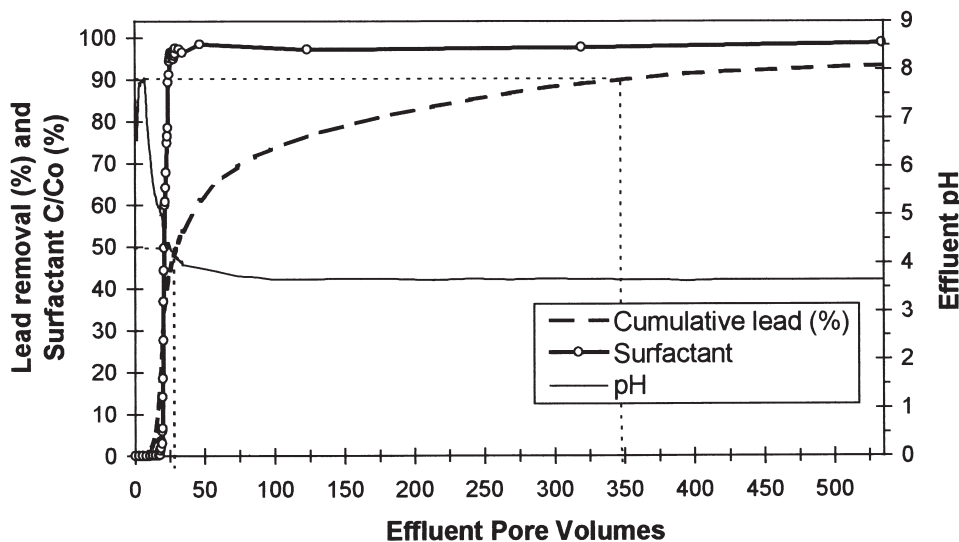


FIGURE 9. Cumulative effluent lead, effluent pH, and ISML breakthrough curve.

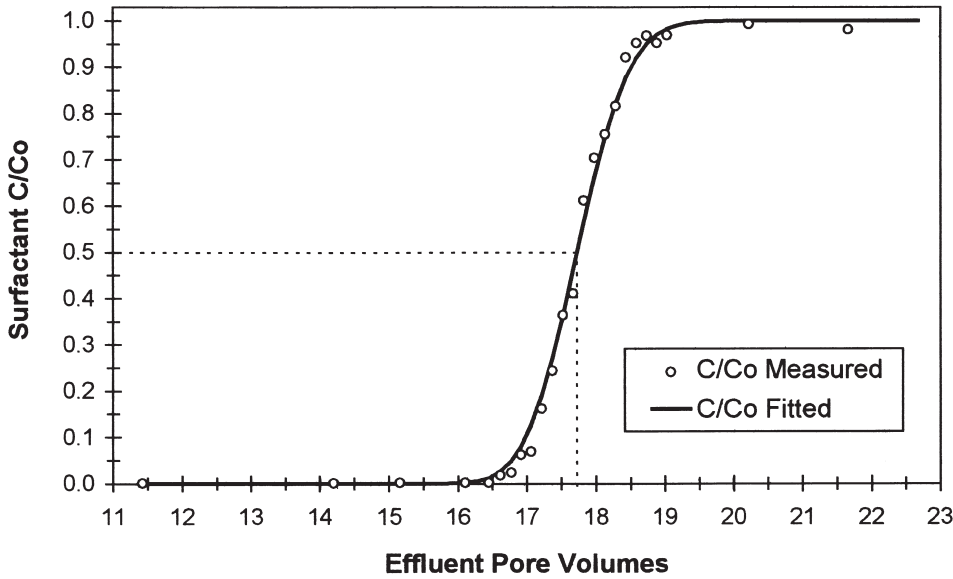


FIGURE 10. Measured and fitted LC breakthrough curves.

$$R = 1 + \rho_b k_d / \varphi \tag{2}$$

where ρ_b is the dry bulk density; and φ is the porosity. Substitution of Equation 2 into Equation 1 yields

$$C^* = C\varphi(R - 1) / \rho_b \tag{3}$$

with $C = 0.025$ mol/L; $\varphi = 0.33$; $\rho_b = 1.78$ kg/L, and the fitted values for R , the adsorbed mass was 0.078 and 0.096 mol/kg for LC and IMSL, respectively. Because both surfactants solutions have a valance of +1, those mass concentrations correspond to 77% for LC and 92% for ISML of the CEC listed in Table 2. The available sites were probably reduced due to loss of soil CEC sites as the soil pH was lowered by the surfactant. At the surfactant adsorption front, surfactant is adsorbed due to cation exchange. The adsorp-

tion front moves forward only after all available adsorption sites are filled.

Although this study did not quantify the soil lead chemistry, known principals provide a guide to the conditions during leaching. Due to the method of lead incorporation and the initial soil pH of 8, it would be expected that most of the lead was initially to be in the form of insoluble lead carbonate solids. As the surfactants lowered pH to 7, carbonate would be consumed and $Pb_4(OH)_4^{4+}$ formed. Such metal hydroxides would be adsorbed on the iron oxide surface sites that are abundant in the Slaughterville (McLean and Bledsoe, 1992). That adsorption is a strong, almost irreversible covalent bond, thus keeping the lead immobile. However, as the pH continued to drop below 7, increasing amounts of the mobile species Pb^{2+} would be created until by pH 5, all accessible lead

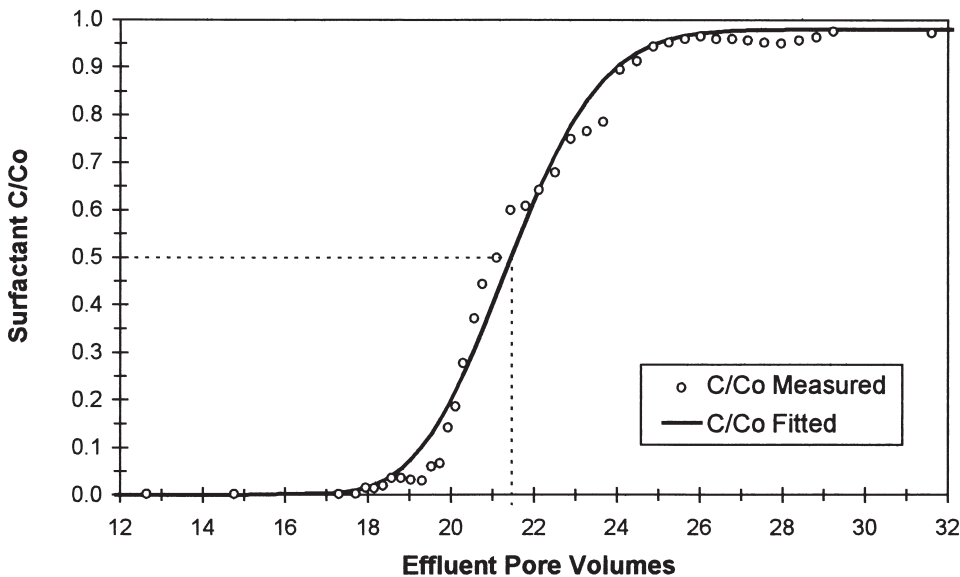


FIGURE 11. Measured and fitted ISML breakthrough curves.

would be in that form (Snoeyink and Jenkins, 1980). At that point, whereas the lead would be mobile, it would still be subject to cation exchange processes.

A large divalent metal such as Pb^{2+} would normally be expected to be preferentially, but reversibly adsorbed to exchange sites. It would be expected that the metal cation would have a relatively large transport retardation coefficient, but instead the lead was eluted relatively quickly due to adsorption site competition from the surfactants. Cationic surfactants adsorption occurs due to cation exchange enhanced by London-van der Waals dispersion forces. Because of 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 (Rosen, 1989). Dispersion forces result from nonsymmetrical position of electrons in a molecule. Every molecule has an instantaneous electric dipole that arises from the fact that in any given moment the electrons are not distributed symmetrically (Kipnis et al., 1996). This dispersion force is a type of intermolecular electrical force, whose magnitude increases with molecular mass. The strength of dispersion forces depends on how readily electrons in a molecule can move about or become "polarized", and the ease of polarization depends on molecular size. Large molecules such as surfactants have more electrons far removed from the nuclei which are relatively easy to polarize. This explains why dispersion forces increase in strength with molecular mass (Masterton et al., 1981). Because lead has a smaller molecular weight than do the surfactants used, it has a smaller net dispersion force. For the surfactants, desorption of lead was more rapid by the higher molecular weight ISML (MW = 503) than LC (MW = 399). According to McBride (1994), organic cations of higher molecular weight are adsorbed on exchange sites with higher selectivity for the larger molecule. This order also may arise from higher entropy value of the exchange reaction because more water molecules gain freedom of motion as they are displaced into solution by the larger cation. At the same time, removal of the larger organic cation from solution lowers the energy of the solution phase, so that energy as well as entropy may drive the exchange process.

The lack of total lead recovery from the soil is probably due to the presence of fulvic and humic acids in the organic matter. These acids will react with lead in soil and form organic acid complexes with strong chemical bonds (Logan and Traina, 1993). Because the mechanism of lead removal by surfactants is based on the electrostatic activities, even at low pH, some lead is in the form of complexes with very strong chemical bonds which is not leachable from soil.

One of the beneficial factors of using cationic surfactants in soil cleanup from heavy metals is that many surfactants do not accumulate in the environment due to their biodegradability. The cationic surfactants used in this investigation were a long-chain fatty acid salt (ISML) and quaternary

ammonium compound (LC). According to Karsa and Porter (1995), after 28 days, 60% of quaternary ammonium salts are biodegraded, whereas fatty acid salts are totally mineralized. Screening tests indicated that the test period necessary for total mineralization varies strongly. Karsa and Porter (1995) state that results from these tests tend to be conservative and underestimate the biodegradation potential in the environment. Therefore, readily biodegradable cationic surfactants such as quaternary ammonium salts and fatty acid salts will not accumulate in most ecosystems.

CONCLUSION ●

This research determined the ability of cationic surfactants to desorb lead from a calcareous soil under saturated conditions and to establish the potential of surfactants use for in situ soil cleanup of heavy metals. Saturated tests results indicated that ISML and LC desorbed 94 and 92% of lead from soil, respectively. Lead desorption was only 1.5% by water and 1.7% by dilute nitric acid. The mechanism of lead desorption and transport process was based on soil acidification and adsorption site competition. The surfactant flow through the column was retarded by factors of 21.5 and 17.7 for ISML and LC, respectively. At a relative concentration of $C/C_0 = 0.5$, ISML and LC removed 35.3 and 0.27% of lead, respectively. Desorption of lead was pH dependent. Throughout the experiment, pH dropped from 7.9 to 3.6 for ISML and 7.9 to 3.7 for LC. The total effluent pore volumes were 582 and 520 for ISML and LC, respectively. Most lead desorption for ISML was observed between 9 and 74 pore volumes after which 70% of lead was removed. Only 1.5% of lead was removed by LC after the same number of pore volumes. Overall, ISML was by far the most effective in removing lead from the Slaughterville soil. Based on these findings, cationic surfactants similar to ISML show promise regarding soil remediation of heavy metals.

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