Evaluation of ethoxylated alkylsulfate surfactants for use in subsurface remediation

Joseph D. Rouse, David A. Sabatini, R. Eric Brown, Jeffrey H. Harwell

ABSTRACT: Experiments were conducted to evaluate the potential of ethoxylated surfactants with degrees of ethoxylation ranging from one to four per molecule for use in subsurface remediation. It was hypothesized that ethoxylated anionic surfactants will exhibit lower losses in the subsurface due to precipitation and sorption as a function of increasing ethoxylation while maintaining high hydrocarbon solubilization potentials. Results demonstrated that no significant precipitation of surfactant and calcium occurred where the degree of ethoxylation was two or greater. Sorption assays demonstrated that these ethoxylated anionic surfactants were less prone to sorption on soil than nonethoxylated anionic and nonionic surfactants. Furthermore, enhancements in solubilization of naphthalene were evidenced with increasing degrees of ethoxylation, and micelle-water partition coefficients were comparable with those of other high-performance surfactants. Microbial degradation assays indicated that these ethoxylated anionic surfactants served readily as substrates, raising concerns relative to their use in subsurface aerobic systems. However, they could be compatible with a treatment train concluded with a biological unit process. Water Environ. Res. 68, 162 (1996).

KEYWORDS: biodegradation, ethoxylation, groundwater, hydrocarbons, remediation, sorption, surfactants.

Subsurface contamination by petroleum products and other organic contaminants via leaky underground storage tanks, spills, dumping, and so on has been a major concern in recent years. Contaminants of considerable interest in recent research can solubilize hydrophobic compounds into solution to levels above their water solubilities (West and Abriola, 1992; Harwell, 1992; Edwards et al., 1992; Palmer et al., 1992; Rouse et al., 1993; Pennell et al., 1993; Stellner et al., 1993; Shiau et al., 1994; Edwards et al., 1994). Ethoxylated anionic surfactants (for example, sodium lauryl ether sulfates) would likewise be expected to be less susceptible to precipitation than single- or small-head group anionic surfactants.

The hypothesis of this research is that ethoxylated anionic surfactants will exhibit reduced losses in the subsurface relative to nonethoxylated counterparts, that this will be a function of increasing ethoxylation, and that high HC solubilization potentials will be maintained for these surfactants. The objectives of this work are to evaluate the effects of increasing ethoxylation of sulfated surfactants with respect to precipitation and sorption losses and solubilization of HC. Vulnerability of these surfactants to aerobic biodegradation will also be investigated. These objectives are met by investigating the formation of surfactant precipitate with a cation as described by the solubility product, Ksp (Stelter et al., 1988); sorption of surfactant on soil as defined by the distribution coefficient, Kd (Palmer et al., 1992), and a maximum or plateau sorption value, km; HC solubilization potential as described by the micelle-water partition coefficient, Kwm (Edwards et al., 1991); and cumulative microbial oxygen uptake (that is, time-dependent biochemical oxygen demand [BOD] responses [Sawyer and McCarty, 1978]). Linear lauryl (dodecyl)-sulfated surfactants with degrees of ethoxylation varying from zero to four per molecule are used to study the influence of head group size and hydrophilicity on surfactant performance.

Materials and Methods

The surfactants used in this research consisted of sodium lauryl ether sulfates of the STEOL (R) series as supplied by Stepan Company (Northfield, Ill.). The STEOLs are linear fatty alcohol ether sulfates and are considered to be biodegradable. They were received in liquid form, generally approximately 25% active, and Miller, 1993; Lupton and Marshall, 1979; Guerin and Jones, 1988; Laha and Luthy, 1991; Laha and Luthy, 1992; Tiethm, 1994; Rouse et al., 1994).

The efficiency of a surfactant-enhanced remedial effort can be negatively impacted by surfactant losses in the subsurface. These losses may be due to sorption onto soil, precipitation with natural hardness in groundwater, and biodegradation by indigenous microorganisms. Because of charge repulsion from negatively charged surfaces, anionic surfactants are potentially more resistant to sorption on sandy and clayey soils than nonionic surfactants. However, the charged nature of anionic surfactants makes them susceptible to precipitation losses. Surfactants with extended polar moieties, however, may be less susceptible to precipitation due to increased water solubility and ionic constraints. This was recently demonstrated for diphenyl oxide disulfonate (DPDS) surfactants (Rouse et al., 1993). Ethoxylated anionic surfactants (for example, sodium lauryl ether sulfates) would likewise be expected to be less susceptible to precipitation than single- or small-head group anionic surfactants.
with sodium chloride levels of approximately 0.1% and sodium sulfate at approximately 0.2%. Characteristics of these surfactants are shown in Table 1. CS-130, CS-230, and CS-330 are typically used in shampoos and bath products, and 4N is used in detergent applications. All of these surfactants are not considered as hazardous materials under current Department of Labor definitions. The well-known sodium lauryl (dodecyl) sulfate (SDF) (NF/FCC grade, Fisher Scientific Co.) was used as a point of comparison, being essentially of the same form as the STEOL series with zero ethoxylation. Unless otherwise noted, all assays conducted at room temperature (approximately 22°C), and deionized water was used for mixing reagents and test samples.

The CMCs were estimated by the capillary rise method (Adamson, 1990) which consisted of measuring meniscus rise in a small-volume pipet (Fisher Scientific Co.; 1/10 mL capacity with markings at 1/1 000 mL and inner diameter of 0.044 61 cm). For each surfactant concentration tested the pipette was wetted with the solution and clamped onto a brace, and the meniscus was allowed to come to a steady level (requiring approximately 5 min) above a reference mark (0.05-mL mark) at the solution surface. Before use, the pipette had been cleaned with concentrated sulfuric acid, rinsed in hydrochloric acid and deionized water, and oven dried. One surfactant solution (CS-230) was also evaluated by the bubble-pressure method with a SensiDyne Surface Tensiometer 6000, calibrated to clean water and ethyl alcohol, which resulted in similar surface-tension values yielding approximately the same CMC as the capillary rise method, thereby corroborating the method.

Naphthalene (Aldrich Chemical Co., 99% purity), a common component of petroleum products, was used as the HC contaminant of interest for solubilization assays. It is reported as having 85% yield, yielding approximately the same CMC as the capillary rise method, thereby corroborating the method.

Sorption experiments were conducted both with and without Ca addition. Samples were shaken mechanically for 24 hours, after which they were centrifuged to remove colloidal soil particles before high-performance liquid chromatography (HPLC) analysis. Samples without Ca addition were not adequately separated by centrifugation and thus were passed through 0.8- and 0.2-μm syringe filters, consecutively, during injection. Soil-water blanks were used to correct for background interferences.

The HPLC analyses were conducted with a Beckman System Gold chromatograph (Beckman Instruments, Inc., San Ramon, Calif.) with a 250 × 4.0-mm Spherisorb C18 reverse-phase column (Scientific Glass Engineering Pty. Ltd., Ringwood, Australia). Anionic surfactants were quantified by HPLC analysis with an Alltech 320 Conductivity Detector (Alltech Assoc., Inc., Deerfield, Ill.) at a flow rate of 0.7 mL/min with a mobile phase of 85% methanol (HPLC grade) mixed with double deionized water (approximately 17.5 Mohms). The HPLC determinations of naphthalene were by either a Waters 486 (Millipore Corp., Milford, Mass.) or Beckman UV absorbance detector (276 nm wavelength) with the same flow rate and mobile phase as above.

Respirometer assays were conducted with a Hach (Loveland, Colo.) manometric apparatus (model 2173B) using Hach BOD nutrient buffer solution and lithium hydroxide to complex carbon dioxide. During assays, samples were stirred gently with magnetic stir bars at approximately 200 rpm. For each concentration of surfactant tested, duplicate samples were run, and for each series tested, duplicate endogenous controls (only nutrients and microbial seed in deionized water) were executed. The microbial seed was obtained from an activated sludge domestic wastewater treatment plant. Sludge samples from the aeration basin were decanted to a suspended solids concentration (Stan

<table>
<thead>
<tr>
<th>Surfactant</th>
<th>Average molecular weight</th>
<th>Average number of ethoxylate units</th>
<th>CMC, mM (g/L)</th>
<th>Micellar surface tension, mN/m</th>
<th>Surface area per molecule, Å²/molecule</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDS</td>
<td>288</td>
<td>0</td>
<td>8.2 (2.4)</td>
<td>39</td>
<td>53</td>
</tr>
<tr>
<td>CS-130</td>
<td>346</td>
<td>1</td>
<td>3.2 (1.1)</td>
<td>35</td>
<td>64</td>
</tr>
<tr>
<td>CS-230</td>
<td>382</td>
<td>2</td>
<td>3.2 (1.2)</td>
<td>35</td>
<td>48</td>
</tr>
<tr>
<td>CS-330</td>
<td>442</td>
<td>3</td>
<td>3.3 (1.4)</td>
<td>35</td>
<td>66</td>
</tr>
<tr>
<td>4N</td>
<td>445</td>
<td>4</td>
<td>2.3 (1.0)</td>
<td>35</td>
<td>44</td>
</tr>
</tbody>
</table>

* Molecular formula, C₉H₈O₇ (C₆H₄O₇SO₄Na, where n = average number of ethoxylate (EO) units.

b Per surfactant molecule.

a Calculated from capillary rise (see text).

b Calculated from surface tension data (see text).

Table 1—Characteristics of anionic surfactants used.
standard Methods 24, Sect. 2540 D, Standard Methods, 1992) of 5.0 g/L. A 2-mL aliquot of this seed was added to each assay sample (approximately 0.5% v/v).

Results and Discussion

Surface tension. Results of capillary rise assays are shown in Figure 1. As seen in Figure 1, with increasing surfactant concentration (and thus decreasing surface tension), the height of capillary rise in the pipette decreased until the CMC was surpassed. Estimations of CMCs from Figure 1 are based on the intersections of straight-line extensions in the declining surface tension region and the constant level or micellar surface tension region (Mukerjee and Mysels, 1971). The CMC values and micellar surface tensions are reported in Table 1. As shown in Figure 1, the surface tensions of micellar solutions of the STEOL surfactants are all similar (approximately 35 mN/m). For the pipette system used here (see Materials and Methods), surface tension (mN/m) equals 3.52 times capillary rise (µL) for method (see Adamson, 1990). Both the CMC and surface tension values reported here for these sulfated surfactants are consistent with values recently reported for other anionic surfactants (Rouse et al., 1992).

Also included in Table 1 are calculations of surface area coverage per surfactant molecule as determined by the Gibbs equation. The values determined here, ranging from approximately 50 to 70 Å²/molecule, are typical of sorption coverage at surface saturation (without a swamping electrolyte) and suggest a somewhat tilted arrangement of surfactant molecules at the interface (Rosen, 1992a).

Precipitation. Figure 2 shows the precipitation responses at 15°C for systems containing STEOLs (lauryl ether sulfate precipitating with Ca). CS-130 had a significant region of positive response with a log Kp of −11.5, as shown in Figure 2. This precipitate was very fine—requiring close observation to detect in many cases. Precipitation assays for SDS (lauryl sulfate precipitating with Ca; data not shown) resulted in a log Kp value of −9.5, which is nearly equal to that obtained previously using sodium dodecylbenzene sulfonate (SDBS) (Rouse et al., 1993). The presence of precipitate as a distinct white floe in the SDS systems was easy to confirm by visual inspection. It was expected that CS-130 should have a higher Kp than SDS because of the ethoxylate unit. The contrary observation, though, may be due to variations in surfactant compositions apart from the reported average molecular design. Furthermore, the appearances of the floes of the two surfactants, as noted, suggest that different forms of precipitation are occurring. Identification of these components and determination of their environmental significance should be addressed in further research.

The precipitation boundary for CS-230, catching the upper boundary of the region tested (log Kp = −7.5), is also shown in Figure 2. CS-330 and 4N had negative precipitation responses throughout the ranges of concentrations shown in Figure 2 (up to 0.1 M Ca). The STEOLs with higher degrees of ethoxylation (2 or greater) compared well with DPDS surfactants, which were also resistant to precipitation (Rouse et al., 1993). It should be noted that the natural hardness of a groundwater would probably lie between −2.5 and −2.0 on the log [Ca] (M) scale, thus CS-230 as well as CS-330 and 4N should all be compatible with most subsurface applications with respect to hardness tolerance.

Sorption on soil. Figure 3 shows the results of sorption experiments. These experiments were conducted with 0.010 N Ca addition to provide a uniform background matrix and to promote separation of solid and liquid phases. However, for systems containing SDS, precipitation with Ca resulted in relatively high surfactant losses (high q values as shown in Figure 3), thus requiring that this surfactant be tested without Ca addition to define losses due to sorption only. Results of precipitation assays clearly indicated that the SDS equilibrium concentrations (Ceq) in Figure 3 are indeed within the zone of precipitation for the Ca addition used; this confirms the precipitation interference. These results demonstrate the possibility of confusing precipitation with sorption as well as the danger posed by precipitation to surfactant-enhanced soil remediation. The SDS sorption assays without Ca addition are used for comparative purposes below.

Figure 2—Precipitation of STEOL surfactants with calcium at 15°C. Legend only addresses CS-130. Precipitation boundary for CS-230 is as shown. CS-330 and 4N did not precipitate within the range of concentrations shown. Log Kp = log( [Ca] ) + 2 ·log [surfactant·M], where molar concentrations are taken from precipitation boundary with negative slope.

Figure 1—Capillary rise versus surfactant concentration with capillary diameter of 0.04461 cm.
For the same reasons stated above, the CS-130 sorption assays with Ca should also have experienced the precipitation interference (see Figure 2). However, the results shown in Figure 3 do not reflect this. By visual observation, though, formation of precipitation was observed in the CS-130 assay samples approximately 1 day after the quantitative analyses were conducted. Evidently, the higher temperature used for the sorption assays versus the precipitation assays (22°C versus 15°C) and possibly energy input from mechanical mixing, resulted in a delayed precipitation response with this surfactant.

Most remedial surfactant applications would use supra-CMC levels to promote contaminant transport. As such, qmax, (the plateau sorption value approached or achieved at higher concentrations) is used as an indicator of surfactant losses due to sorption. Langmuirian analysis of relatively high Ce values was used to determine plateau sorption values (qmax). The qmax values serve as estimates of pseudplateau values for Ce levels beyond the CMC and are in keeping with a qualitative assessment of Figure 3. As shown in Table 2, the STEOLs have much lower supra-CMC sorptive losses with the same soil than anionic surfactants without extended polar head groups. Furthermore, they are comparable with a DPDS surfactant (Table 2), which has been shown in previous research to be considerably less sorptive than nonionic surfactants (Rouse et al., 1993).

It is clear from visual inspection of Figure 3 that the STEOLs experience much less sorption than SDS (the sorption values q are lower at any given equilibrium concentration). Fundamentally, surfactant sorption has been observed to evidence up to four regions of sorption (Rosen, 1989a; Nayyar et al., 1994; Edwards et al., 1994). However, surfactant sorption on soils has been quantitatively assessed using the Langmuir sorption model to determine qmax values (Pennell et al., 1993) and the linear sorption model to describe monomer sorption at low concentrations (Palmer et al., 1992). To facilitate comparison of sorption results within this study and with results from previous research using the same soil, these approaches are used herein. However, it should be cautioned that use of these parameters in predicting surfactant sorption for soils and/or concentrations different from those used here could result in inaccurate estimates.

Table 2—Surfactant losses due to sorption on soil.*

<table>
<thead>
<tr>
<th>Surfactant</th>
<th>qmax g/g</th>
<th>Kd cm³/g⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDS</td>
<td>0.00721</td>
<td>ND</td>
</tr>
<tr>
<td>CS-130</td>
<td>0.00290</td>
<td>8.3</td>
</tr>
<tr>
<td>CS-230</td>
<td>0.00126</td>
<td>6.3</td>
</tr>
<tr>
<td>CS-330</td>
<td>0.00052</td>
<td>4.6</td>
</tr>
<tr>
<td>SDBS</td>
<td>0.0114</td>
<td>8.3</td>
</tr>
<tr>
<td>C-12-POGS</td>
<td>0.0016</td>
<td>3.1</td>
</tr>
<tr>
<td>CA-620</td>
<td>not evaluated</td>
<td>10.8</td>
</tr>
<tr>
<td>CA-820</td>
<td>not evaluated</td>
<td>41.1</td>
</tr>
<tr>
<td>CA-530</td>
<td>not evaluated</td>
<td>31.2</td>
</tr>
<tr>
<td>CA-660</td>
<td>not evaluated</td>
<td>19.7</td>
</tr>
</tbody>
</table>

* Soil:water ratio = 1g:5ml.
* Sodium dodecylbenzene sulfonate, same media (Rouse et al., 1993).
* Dodecyl benzene sulfonate, same media (Rouse et al., 1993).
* Nonionic surfactants (alkylphenol polyoxyethyleneates), same media (Palmer et al., 1992).
* ND = not quantified due to difficulty in identifying a clearly linear region.

The Kd values provide valuable information about monomer surfactant sorption activity when low-surfactant concentrations are considered and, as shown in Table 2, the anionic surfactants tested here and elsewhere typically have lower Kd values and thus less monomer sorption than has been demonstrated for nonionic surfactants (Palmer et al., 1992). Thus, for sub-CMC applications less overall sorption is observed for STEOLs compared with SDBS and various nonionic surfactants (consistent with results for DPDS, Rouse et al., 1993). These results, coupled with the precipitation assays, corroborate our hypothesis that extended polar head group anionic surfactants are less susceptible to losses in subsurface environments than conventional anionic or nonionic surfactants. These same fundamental phenomena governing sorption mechanisms will hold true for other soil media, except where a medium with a significant positive charge is of concern, such as in an environment with carbonate minerals (Tabatabai et al., 1993).

Solubilization of naphthalene. Results of solubilization assays for all surfactant-naphthalene systems are shown in Figure 4.

![Figure 3](image-url) - Sorption of anionic surfactants on soil (CRA). Mass of surfactant sorbed per mass of soil (q) is plotted as a function of the equilibrium surfactant concentration (Ce) in solution.

![Figure 4](image-url) - Solubilization of naphthalene by anionic surfactants.
Table 3—Solubilization of naphthalene.

<table>
<thead>
<tr>
<th>Surfactant</th>
<th>MSR</th>
<th>Log $K_m$</th>
<th>WSR</th>
<th>Log $K_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDS</td>
<td>0.068</td>
<td>4.25</td>
<td>0.0903</td>
<td>3.06</td>
</tr>
<tr>
<td>CS-130</td>
<td>0.108</td>
<td>4.33</td>
<td>0.0400</td>
<td>3.07</td>
</tr>
<tr>
<td>CS-230</td>
<td>0.127</td>
<td>4.40</td>
<td>0.0426</td>
<td>3.13</td>
</tr>
<tr>
<td>CS-330</td>
<td>0.143</td>
<td>4.44</td>
<td>0.0416</td>
<td>3.09</td>
</tr>
<tr>
<td>4N</td>
<td>0.126</td>
<td>4.39</td>
<td>0.0882</td>
<td>3.04</td>
</tr>
<tr>
<td>SDDS*</td>
<td>0.062</td>
<td>4.04</td>
<td>0.0190</td>
<td>2.76</td>
</tr>
<tr>
<td>C10-DPDS*</td>
<td>0.054</td>
<td>4.06</td>
<td>0.0126</td>
<td>2.50</td>
</tr>
<tr>
<td>C12-DPDS*</td>
<td>0.104</td>
<td>4.32</td>
<td>0.0233</td>
<td>2.95</td>
</tr>
<tr>
<td>C16-DPDS*</td>
<td>0.132</td>
<td>4.41</td>
<td>0.0263</td>
<td>2.90</td>
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<tr>
<td>Brij 30*</td>
<td>0.317</td>
<td>4.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA-720*</td>
<td>0.323</td>
<td>4.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NP-10*</td>
<td>0.385</td>
<td>4.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-100*</td>
<td>0.338</td>
<td>4.64</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Anionic surfactants (Rouse et al., 1993).
* Nonionic surfactants (Edwards et al., 1991).

Table 3 summarizes these results, where the molar solubilization ratio (MSR) is determined as the slope of the isotherm beyond the CMC and log $K_m$ (a function of MSR) is the micellar-water partitioning coefficient (on a molar basis) (Edwards et al., 1991). Also included in Table 3 are weight solubilization ratios (WSRs), which are obtained by analyzing the same data on a weight basis (that is, both coordinates in mg/L). Analogous to $K_m$, a micellar-water partition coefficient on a weight basis ($K_p$) can be derived (Rouse et al., 1993). Analysis of results on a weight basis can be beneficial when practical issues such as purchasing materials and field application are considered.

Because of the polar organic nature of the ethoxylate units in the outer palisade layer or mantle of the micelle, it is reasonable to conjecture that solubilization of naphthalene (a polarizable organic compound due to its aromatic nature) into the outer layer of the micelle would supplement the dominant effect of partitioning into the hydrophobic core of the micelle. Furthermore, Diallo et al. (1994) suggested that hydrogen bonding between aromatic hydrocarbons and water molecules bound to surfactant ethoxylate units, as well as dehydration of ethoxylate chains with subsequent electron donor-acceptor complexation of aromatic HCs and ethoxylate units, may be possible mechanisms for enhancement of solubilization capacity. Step increases in MSRs with increasing ethoxylation for 0, 1, 2, and 3 units were indeed evidenced (Table 3) (statistically significant with a 95% confidence level). However, the STEOL with approximately 4 ethoxylate units (4N) failed to follow this trend. Difficulties arise, though, in making these comparisons, where commercial production methods can result in product variations from their intended design values (average degree of ethoxylation, sterylization, and so on; ante irregular trend in MWs in Table 1). Furthermore, with alterations in surfactant structure or size, micellar aggregation numbers could change, resulting in different sizes and shapes of micelles, all of which could effect solubilization potential (Rosen, 1989b).

Perhaps the best observation is that the solubilization results for CS-230 and CS-330 are not greatly different, and they are superior to the others when molar and weight-based parameters are collectively considered. Furthermore, these results compare well with results of naphthalene solubilization by other high performance anionic (Rouse et al., 1993) and nonionic (Edwards et al., 1991) surfactants (Table 3).

Biodegradation of surfactants. Results of respirometric assays for SDS and the STEOLs (used to provide a preliminary assessment of surfactant biodegradability) are shown in Figures 5 and 6, respectively. As shown, these surfactants served readily as substrates. For the SDS samples (Figure 5), there appears to be a general trend for oxidation rates to decrease with increasing surfactant concentration, perhaps because of a toxicity effect. The deviation from this trend with the highest SDS concentration (38.6 mM exerting a higher BOD than the 14.3 mM) could be due to the offsetting effect of an increasing concentration of a labile impurity (for example, unsulfated alcohols) in the composite surfactant. It should be noted that species in the microbial seed may differ in their responses to the presence of the surfactant and associated impurities; this obviously complicates the interpretation of the results.

For the STEOLs (Figure 6), there is an increase in time before onset of oxidation (lag time) for assays with surfactant levels greater than the CMC. For CS-130, the oxidation response with increasing surfactant concentration is similar to that observed for SDS. Perhaps the similar molecular size of these surfactant types leads to a similar response. For CS-330, however, the oxidation response continually increases with increasing surfactant concentration (over a range of 2 orders of magnitude spanning the CMC).

It can be expected that some components of a surfactant (for example, ethoxylate units), may serve readily as substrates, thus initially exerting a high-oxygen demand. This response would most likely be followed by a more gradual degradation of more recalcitrant components (for example, alkane chains). Accordingly, the increase in oxygen demand with increasing concentrations of the CS-330 could be a reflection of its higher degree of ethoxylation. Furthermore, some component of the surfactant (for example, the sulfate group) could be vulnerable to fortuitous enzyme activity that would generate an oxygen demand but not benefit the microorganisms. The above effects could explain the results for higher concentrations of CS-130 and CS-330 that approached plateau oxygen demands well below their theoretical demands.

![Figure 5](image_url)—Microbial oxidation of SDS at various concentrations. 1.0 mM of SDS has a theoretical BOD of 584 mg/L. All data points are averages of duplicate assays.
Figure 6—Microbial oxidation of CS-130 and CS-330 at various concentrations. 1.0 mM CS-130 has theoretical BOD of 664 mg/L. 1.0 mM CS-330 has theoretical BOD of 774 mg/L. Endogenous controls (not shown) had 120-hour BODs of approximately 7 mg/L. All data points are averages of duplicate assays.

A certain degree of recalcitrance to biodegradation of a surfactant is desirable, that is, the surfactant must survive long enough to perform its intended function (transport of contaminant, enhancement of bioavailability, and so on) before its demise. Another class of high performance anionic surfactants (DPDSs, Rouse et al., 1993) that are classified as biodegradable did not serve as substrates under the same testing conditions used here (Rouse et al., 1995). Further research under more environmentally realistic conditions (for example, soil systems) for extended periods of testing would be necessary to evaluate suitability for surfactant applications in the field. In the case of the STEOLs, perhaps a surfactant-enhanced pump-and-treat scheme without promotion of in situ microbial activity followed by above ground biological treatment for removal of both contaminant and surfactant would be feasible. Also, subsequent to a pump-and-treat effort, residual surfactant in the subsurface could be degraded by stimulation of microorganisms (that is, nutrient addition). Potentially, the surfactant could also serve as a cosubstrate, thus enhancing the removal of trace levels of contaminant. These ideas could serve as potential avenues for further research.

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References


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