FINAL REPORT

SURFACTANT DEVELOPMENT FOR ENHANCED OIL RECOVERY

GRANT NO. DE-FG22-93MT93007

Prepared by:
The Morgan State University
Fossil Energy Consortium

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Objective: The general objective of the project is to develop novel surfactants for tertiary recovery of light oil at elevated temperatures and high brine concentrations. Specific objectives are: to design, synthesize and characterize new surfactants capable of forming microemulsions of high stability at high temperatures and high salinity; to select microemulsions that will yield optimum efficiency and effectiveness in oil solubilization; to characterize the physico-chemical properties of selected microemulsion; to correlate surfactant efficacy with physico-chemical variables of selected reservoirs.

Project Description: The Morgan State University Fossil Energy Consortium comprised of Morgan State University, South Carolina State University, the Institute for College Research Development and Support, and the Phillips Petroleum Company, as a private sector collaborator, proposed to undertake a research project to develop novel surfactants for tertiary oil recovery. The novel surfactants will include highly branched single, double and triple-tailed alkyl halides and aryl sulfonates. Additionally, anionic and nonionic surfactants such modified homologues of ethoxylates will be investigated. These surfactants will be synthesized, characterized and tested for their effectiveness for use in tertiary oil recovery. The tests will include viscosity measurements, surface/interfacial tension measurements and microstructural studies of microemulsions of the surfactants using HNMR, fluorescence techniques and conductivity measurements. The efficacy of the surfactants will be correlated with physico-chemical variables of selected reservoirs. It is anticipated that the results of the research effort will produce surfactants that will be both economical and directly applicable in the industry.

Background: The term surfactant is an acronym for surface active agent. Surface active agents are categorized as amphiphilic compound containing hydrophobic tails and hydrophilic heads. The general properties of all surfactants reside in: (1) their ability to spontaneously aggregate to form micelles if the solvent is water. If the solvent is organic or non-polar, the surfactants form inverted or reverse micelles; (2) their behavior as emulsifying agents in a mixture of two immiscible solvents; (3) their ability to drastically reduce the surface tension of solvents and (4) their high ability to solubilize species such as...
oil, water, neutral or charged particles. Further properties of surfactants are their potential
to solubilize oil in microemulsion formations, their potential in producing an ultra low
surface tension, and their ability to adsorb at the oil-water interphase. The adsorption
property is enhanced in the presence of electrolytes or brines. These select properties
make surfactants ideal candidates for use in tertiary oil recovery projects.

Techniques and Approaches
A. Surfactant Synthesis: Surfactants with longer chain length of carbon atom greater
than 12 are known to have greater surface activity including better surface adsorption.
This is also true of surfactants with large head groups. Although surfactants with smaller
head groups were synthesized and characterized in the work, but efforts were
concentrated in the synthesis of quaternary alkyl ammonium bromide surfactants with
carbon chain length of 16 or greater and those with bulky head groups including those of
benzyl groups. It was found during the course of this work that double chain surfactants
were very effective in terms of oil solubility and surface tension reduction. For these
reasons, very many double-tailed surfactants were also synthesized. The general structure
of the surfactants that dominated this work is:

$$R-N^+-R_2^\text{X}^-$$

$R =$ Normal linear alkyl chain with carbon atom number, $n$, equal to 16
$R' =$ Normal linear alkyl chain with carbon atom number, $n$, equal to or greater than 12
  up to 16
$R'' =$ Methyl group
$X =$ Bromide or Chloride.

Double chain surfactants with two dissimilar tail groups were also synthesized. In this
case the $R'$ in the above general formula is $(\text{CH}_3)_3\text{C-phenyl-(OCH}_2\text{CH}_2)_2$.

Single chain sulfonates and double chain surfactants of magnesium, calcium, barium and
strontium were also synthesized. The synthesized surfactants are grouped as shown on
Table 1.

Table 1. Selected List of Surfactants, $\text{CH}_3(\text{CH}_2)_15^N^+\text{RR'}_2^\text{Br}^-$ Synthesized.

<table>
<thead>
<tr>
<th>Group</th>
<th>$R$</th>
<th>$R'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\text{C}_2\text{H}_5$</td>
<td>$\text{C}_2\text{H}_5$</td>
</tr>
<tr>
<td>2</td>
<td>$\text{CH}_3(\text{CH}_2)_2$</td>
<td>$\text{CH}_3(\text{CH}_2)_2$</td>
</tr>
<tr>
<td>3</td>
<td>$\text{CH}_3(\text{CH}_2)_3$</td>
<td>$\text{CH}_3(\text{CH}_2)_3$</td>
</tr>
<tr>
<td>4</td>
<td>$\text{CH}_3(\text{CH}_2)_4$</td>
<td>$\text{CH}_3(\text{CH}_2)_4$</td>
</tr>
<tr>
<td>5</td>
<td>$\text{CH}_3(\text{CH}_2)_5$</td>
<td>$\text{CH}_3(\text{CH}_2)_5$</td>
</tr>
</tbody>
</table>
Table 1 Continued

**Group II**

| 6.  | CH₃(CH₂)₁₁ | CH₃ |
| 7.  | CH₃(CH₂)₁₂ | CH₃ |
| 8.  | CH₃(CH₂)₁₃ | CH₃ |
| 9.  | CH₃(CH₂)₁₄ | CH₃ |
| 10. | CH₃(CH₂)₁₅ | CH₃ |

**Group III**

\[ R^-N^+--R_2'Cl^- \]

<table>
<thead>
<tr>
<th>R</th>
<th>R'</th>
<th>R''</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₃(CH₂)₁₁</td>
<td>CH₃</td>
<td>(CH₃)₃C-phenyl-(OCH₂CH₂)₂</td>
</tr>
<tr>
<td>CH₃(CH₂)₁₅</td>
<td>CH₃</td>
<td>(CH₃)₃C-phenyl-(OCH₂CH₂)₂</td>
</tr>
</tbody>
</table>

**Group IV**

\[ R_2M^{2+}2Cl^- \]

<table>
<thead>
<tr>
<th>R</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>[CH₃(CH₂)₁₃SO₃]₂</td>
<td>Ca</td>
</tr>
<tr>
<td>C₁₂H₂₅-phenyl-SO₃</td>
<td>Ca</td>
</tr>
<tr>
<td>&quot;</td>
<td>Mg</td>
</tr>
<tr>
<td>&quot;</td>
<td>Ba</td>
</tr>
<tr>
<td>&quot;</td>
<td>Sr</td>
</tr>
</tbody>
</table>

**Methods of Preparation**

**Groups I and II** The surfactants in groups I and II were prepared by heating a solution of RBr and R'NR"₂ in acetonitrile at reflux for at least 24 hours. (This method was developed by Buckingham, Garvey and Warr, J. Phys. Chem., 1993, 97, 10236-10244). The first compound in group I crystallized when the reaction mixture was cooled, and was recovered by vacuum filtration. In other cases, the solvent was removed and the residue was stirred with diethyl ether before the product was isolated by vacuum filtration. If the resulting material was not virtually colorless, it was recrystallized from ethyl acetate-diethyl ether. The yield in each case ranged from 70 to 90%. The melting ranges of the surfactants were determined and was 30° or less as an indication of satisfactory purity.

Group III: The reaction scheme which is common to both surfactants in this group is as follows, using the C-12 homologue:

\[
(CH_3)_3C_6H_4OH + NaOH \rightarrow (CH_3)_3C_6H_4ONa
\]

\[
2 + \text{ClCH}_2\text{CH}_2\text{OCH}_2\text{CH}_2\text{Cl} \rightarrow (CH_3)_3C_6H_4\text{OCH}_2\text{CH}_2\text{OCH}_2\text{CH}_2\text{Cl}
\]

\[
4 + (CH_3)_2N(CH_2)_{11}CH_3 \rightarrow (CH_3)_3C_6H_4(OCH_2CH_2)_2N^+(CH_3)_2Cl^-
\]

\[
\text{CH}_3(CH_2)_{10}CH_2
\]

The synthesis of 4 was carried out by the procedure of Brunson (U.S. Patent, 2,115,250). 1 was converted to its sodium salt 2 by treatment with aqueous sodium hydroxide. 3 was added, and the mixture was stirred and heated at reflux for 6.5 hours. The temperature of the mixture was 110°C during the reflux period. The mixture was filtered by gravity and subjected to vacuum distillation. After removal of unreacted 3, the product, 4, distilled at 176-180°C (8 mm) as a clear colorless liquid.

This product was reacted with 5 according to the procedure of Buckingham, et al. (J. Phys. Chem., 97, 10236-10244, 1993). A mixture of 4, 5 and acetonitrile was stirred under reflux for 24 hours. The mixture was allowed to cool to room temperature, and the solvent was removed on a rotary evaporator. The residue was stirred with ether to give a colorless solid which proved, upon vacuum filtration to be extremely hygroscopic. Therefore, ether was removed in vacuo. The product, 6, was stored under nitrogen in a desiccator until needed. The surfactants in this group were obtained in good yield and the purity was determined via potentiometric method as described above.

Group IV: The synthesis of the surfactants in this group involved the direct reaction of the sulfonates with the appropriate metal chloride using the method of Reed and Tartar (J. Am. Chem. Soc., 1936, 58, 322). A slight modification in the procedure was made in order to improve the yield. A weighed amount of the sulfonic acid was dissolved in water in a 250-mL beaker. Appropriate amount of the metal chloride was dissolved in a small vial and added to the stirred solution in the beaker. The mixture was heated to 90°C and allowed to cool to room temperature. The solid particles that were formed were vacuum filtered using a medium porosity filter paper. It was then transferred to a crystallizing dish and placed in a vacuum desiccator for 2 hours. The yield in each case was better than 90% with purity of 97 or better.
B. Screening: One of the important properties of a surfactant is its ability in the reduction of surface tension of a medium in which it is solubilized. This property is a critical parameter in enhanced oil recovery projects. Surface tension of a system decreases with an increase in the concentration of an added surfactant. This concentration dependence of surface tension continues to a minimum point at which further surfactant increase produces no further reduction in surface tension. This point is referred to as the Critical Micelle Concentration, CMC. The CMC of a surfactant is also determined by conductance method. Both the surface tension technique and the conductance method usually give CMC values that are in very good agreement with each other. For this reason the CMC, as a screening criterion, was measured with either of the two techniques and sometimes in combination of the two. In one instance fluorometric method was used. Table II lists the observed CMC of surfactants selected for screening. The number for each surfactant refers to the number as given on Table I.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$10^4$CMC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>By Conductance</td>
</tr>
<tr>
<td>1</td>
<td>7.30</td>
</tr>
<tr>
<td>2</td>
<td>5.30</td>
</tr>
<tr>
<td>3</td>
<td>2.40</td>
</tr>
<tr>
<td>4</td>
<td>1.42</td>
</tr>
<tr>
<td>5</td>
<td>1.32</td>
</tr>
<tr>
<td>6</td>
<td>1.53</td>
</tr>
<tr>
<td>7</td>
<td>1.24</td>
</tr>
<tr>
<td>8</td>
<td>1.01</td>
</tr>
<tr>
<td>9</td>
<td>0.65</td>
</tr>
<tr>
<td>10</td>
<td>0.49</td>
</tr>
<tr>
<td>11</td>
<td>1.54</td>
</tr>
<tr>
<td>12</td>
<td>0.20</td>
</tr>
<tr>
<td>13</td>
<td>0.15</td>
</tr>
</tbody>
</table>

It can be seen that the CMC of compounds 1 through 10 decreased either as the headgroup is increased or as the secondary chain, in the case of double-tailed surfactants, is increased. The CMC values of compounds 11 and 13 are questionable due to solubility problems. Baring these three surfactants, it can be seen that compounds 10 and 12 show very low CMC values and consequently exhibit very low or ultralow surface tension. Although, other screening criteria were tested for the other surfactants, (Technical reports 2 through 6), but their effectiveness in oil uptake or high salinity tolerance were not as satisfactory as compounds 10 and 12. It will also be noted that these compounds are double-tailed surfactants. However, while compound 10 have similar tail groups, compound 12 has dissimilar tail groups as can be seen from Table I. In view of their apparent satisfactory properties, further screening was conducted on their efficacy in enhanced oil recovery.
Compound 10: \((\text{C}_{16}\text{H}_{33})_2\text{N}^+\text{(CH}_3)_2\text{Br}^-\) (DHDAB)

**Influence of Electrolyte on the Production of Surfactant Middle Phase.**

As stated earlier, surface tension reduction is a very important parameter in any tertiary oil recovery project. This reduction in surface tension is known to be very pronounced in the middle phase microemulsion, which is usually observed when electrolytes are dissolved in a given microemulsion system, usually containing a cosolvent or cosurfactant and electrolyte. Shown on Table 3 is the observed ratio of oil (hexane) volume, \(V_o\), to aqueous surfactant volume, \(V_s\), when 1.0 g of different electrolytes is dissolved in the studied microemulsion.

<table>
<thead>
<tr>
<th>Electrolyte (5.64 %)</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium Chloride (NaCl)</td>
<td>1.5</td>
</tr>
<tr>
<td>Calcium Chloride (CaCl_2)</td>
<td>2.0</td>
</tr>
<tr>
<td>Aluminum Chloride (AlCl_3)</td>
<td>2.86</td>
</tr>
<tr>
<td>Sodium Carbonate (Na_2CO_3)</td>
<td>8.90</td>
</tr>
<tr>
<td>Calcium Carbonate (CaCO_3)</td>
<td>8.50</td>
</tr>
<tr>
<td>No Electrolyte</td>
<td>9.30</td>
</tr>
</tbody>
</table>

By the definition of \(S\), it can be seen that one would want its value to be very low which will correspond to a high volume of a middle phase (surfactant phase) in a given surfactant. From Table 3 it can be seen that sodium chloride produced the lowest value of \(S\). This observation is consistent with the findings of other workers (D.O. Shah, Macro- and Microemulsions, Theory and Practice, ACS Publication, Washington, D.C., 1985, Chapter 11 and D.O. Shah and R.S. Schecter, Improved Oil Recovery by Surfactant and Polymer Flooding, Academic Press, New York, 1977, pp 410-415). It is noteworthy that in these data neither a cosolvent nor a cosurfactant is used. This leads one to speculate that the secondary chain may be playing the role of a cosurfactant. This could prove to be an added advantage in using a double-chain surfactant for enhanced oil recovery technology.

**Salinity Test**

In view of the result described above sodium chloride was chosen for a salinity scan study using compound 10 (DHDAB). In the salinity test the oil and water volumes were kept constant at 10.0 cm\(^3\), respectively, while the surfactant weight was kept constant at 0.1148 g or 0.69 %. The sodium chloride weight was varied from 0.5 g to 5.0 g (2.90 - 23.03 %). Figure 1 shows the observed \(S\) values versus weight percent of sodium chloride.
Figure 1
Plot of \( S \) Vs Weight % Sodium Chloride

Again, in this figure the observed profile is reminiscent of salinity curve of emulsion systems consisting of cosolvents or cosurfactants. In fact, all the double chain surfactants shown on Table I and II display this type of salinity curve. As can be seen from this figure two minima occurred at sodium chloride weight percent of 13.0 and 21.20. These correspond to volume of surfactant of 3.2 and 8.5 cm\(^3\), respectively. This large volume of the middle phase is indeed very encouraging for it guarantees very low surface tension of this system at the given conditions (0.69 % surfactant, 21.2 % sodium chloride at equal volumes of hexane and water). However, salinity tolerance for this system was observed to have been reach at salt concentration of 21.2 %.

**Temperature Effect**

Table 4 lists the observed \( S \) between the temperature range of 50-64 °C as the weight of surfactant is increased. In this experiment the weight of sodium chloride was kept constant at 5.0 g.
Table 4 shows that, even though the weight of surfactant is increasing, the volume of the middle phase is in fact not increasing, but rather decreasing. It was also observed that at these conditions inversion takes place, that is, the surfactant dissolves in the oil phase with the saline phase being very clear with concomitant salt precipitation. This also gives added indication that at the salt concentration used, the salinity tolerance level was reached.

**Emulsion of Burbank Crude Oil with DHDAB**

**Influence of Surfactant Concentration on the Oil Uptake**

DHDAB was used to emulsify a crude oil, Burbank Oil, and to study the uptake of oil of the emulsion. In this experiment the volumes of oil and water were each kept constant at 5.0 cm$^3$. Figure 2 shows a plot of the observed volume fraction of oil to water as a function of surfactant concentration. As can be seen in this figure, the observed ratio decreased asymptotically as the surfactant concentration is increased. This means a steady solubilization of oil into the aqueous phase of the emulsion.

**Figure 2**

*Influence of Surf. on Oil Solubility*

Vol. Oil = 5 mL; Vol Water = 5.0ml
However, when a cosurfactant, n-butyl alcohol, was added to the system, an opposite effect was observed. See Fig. 3. This figure shows an increase in the ratio of volume fraction of oil to water up to the surfactant concentration of about 1.7%, at which point there was equal volume of oil and water.

**Figure 3**

*Influence of n-Butanol on Phase Behavior of Oil; Oil=5 mL; n-BuOh=5 mL, H2O=15 mL*

Beyond this point, at 2.5%, the increase in the water uptake was again observed. It is remarkable to observe that, although the volume of water was three times more than that of the alcohol, the observed volume of the oil phase was much high. In this case, also, the surfactant was mainly solubilized in the oil phase, in direct contrast to what was observed in the absence of alcohol.
Influence of Salt

As stated earlier, NaCl, in the presence of DHDAB-water-hexane produced a high volume of middle phase. When Burbank crude oil was used instead of hexane, it was observed that it is not only that a very high middle phase volume was obtained, the system showed a remarkable ability to tolerate very high concentration of salt. Figure 4 shows a profile of the volume fraction of oil to surfactant. In this experiment, the surfactant-salt weight ratio was kept constant at 0.2. The aqueous volume fraction was kept constant at all salt concentrations at 0.6. As can be seen in this figure, there is shown an asymptotical increase in the ratio of the volume fraction of oil to surfactant as the salt concentration increases. Up to 4.0 grams (15.0 %) of salt was used with no visible precipitation of the salt.

Figure 4

Influence of Surf. on Oil Solubility
Vol.: Oil=5 mL; Water=15 mL; Buoh=5 mL

\[
\begin{array}{|c|}
\hline
\text{Wt. \% of Salt (NaCl)} \\
2.80 & 5.60 & 8.40 & 11.20 & 14.00 \\
\hline
\end{array}
\]
Rheology of the Burbank Crude Oil Emulsified by DHDAB

Rheological study of the emulsion formed by the Burbank Crude oil and DHDAB was also made. Figures 5 and 6 show that the system exhibits non-Newtonian behavior. This is manifested by the shear-thinning profile observed when the observed viscosities were plotted against shear rates.

**Figure 5**

Rheology of Burbank Oil

14% Oil, 15 mL 0.02 M Surfactant

The viscosity decreases as the rate of shear increases. A plot of shear rate versus shear stress also help to confirm the non-Newtonian neoplastic structure of this system.
Figure 6
Rheology of Burbank Oil
14% Oil, 15 mL 0.02 M Surfactant

Compound 12:

\[ C_{16}H_{33}-N^+-(CH_3)_2Cl^- \text{ (BDHC)} \]

\( (CH_3)_3C\text{-phenyl-}(OCH_2CH_2)_2 \)

Salinity Measurement
In the fifth quarterly report it was shown that BDDC, a lower homologue of BDHC showed remarkable tolerance of the electrolyte, sodium carbonate, \( Na_2CO_3 \), and also enhanced greater production of the middle phase and enhanced oil solubility. On the other hand, \( NaCl \) showed little ability for enhanced oil solubility in this surfactant medium. BDHC, being a higher homologue of BDDC was tested for oil uptake in the presence of \( NaCl \). Table 5 shows the influence of oil phase as a function of the weight of \( NaCl \). In this experiment equal volumes of water and oil (hexane) was kept constant at 10.0 cm\(^3\). The concentration of surfactant in the aqueous phase was 0.02 M.
Table 5. Salinity Data for BDHC

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Isotropic phase</td>
<td>9.0 cm³</td>
<td>9.0 cm³</td>
</tr>
<tr>
<td>0.5</td>
<td>9.0 cm³</td>
<td>9.0 cm³</td>
<td>2.0 cm³</td>
</tr>
<tr>
<td>1.0</td>
<td>11.5 cm³</td>
<td>9.5 cm³</td>
<td>0 cm³</td>
</tr>
</tbody>
</table>

The observation from this table is that one phase of the emulsion was observed in the absence of an electrolyte. Upon addition of sodium chloride, a phase separation occurred. However, at low sodium chloride concentration, appreciable volume of the surfactant phase was observed. As the percentage concentration of the electrolyte is increased to 5.7, solubility of the surfactant occurred mainly in the aqueous phase. It was observed that phase inversion occurred between 3% and 5.7% of the sodium chloride concentration. Addition of a cosurfactant, n-pentanol, remarkably enhanced a middle phase production.

**Ekofisk Crude Oil Emulsified by BDHC**

**Effect of Oil Volume on Emulsion Viscosity**

The Ekofisk oil as well as the Burbank Oil discussed above is a crude oil supplied by Phillips Petroleum, a private sector member of the Morgan State Fossil Energy Consortium. The crude oil was used to study the viscosity of the emulsion formed in the presence of BDHC. Volumes of oil ranging from 1.0 cm³ to 7.0 cm³ was added to 15.0 cm³ of 0.02 M BDHC in a 50.0-cm³ Erlenmeyer flask. The emulsion was shaken for about one hour at 400 rpm using Burrell Wrist Action Shaker. After equilibration for another one hour, it was transferred to an UL-adapter for viscosity measurement using Brookfield Digital Viscometer, Model DVII+. Figure 7 shows the observed viscosity plotted against the oil volume fraction at different shear rates.
Figure 7

Viscosity Vs Oil Volume Fraction
at Various Shear Rates

△ 0.37  ◆ 0.73  ○ 1.83  + 3.67  ▲ 6.12  ● 7.34
As can be seen from this figure, viscosity was very high at low oil volume fraction. However, at high oil volume fraction the viscosity decreased to a constant value at all shear rates. This indicates that the emulsion viscosity is dispersed-phase controlled. At the oil volume fraction of 0.21, the viscosity, at all shear rates, leveled off at about 58.0 cP.

Effect of Viscosity as a Function of Shear Rate at Different Temperatures

Figure 8 shows a plot of viscosity obtained at different shear rates at different temperatures. In this study, the volume fraction of oil was kept constant at 0.12.

Figure 8

Viscosity Vs Shear Rate at Various Temperatures, °C

As can be seen from this figure, the emulsion showed a pseudoplastic behavior at all temperatures at very low shear rates. However, at shear rates greater than 1.70 per second, the emulsion appears to be Newtonian at all temperatures. This is indeed very good for
enhanced oil recovery project for, at the range where Newtonian behavior was observed, the viscosity is still moderate, about from 12.0 cP to 50.0 cP, depending on the temperature. This is fairly satisfactory for, at this range, the viscosity is neither too high nor too low, for effective solubilization of oil and its flow.

**Conclusion**

We have shown in this work that double-chain surfactants proved to be very amenable towards enhanced oil recovery projects. Two types of double-tailed surfactants were found to be particularly suitable. One contains similar tailgroups (linear alkyl chains) and the other contains dissimilar tail groups (one tail is normal linear alkyl chain and the other group is branched alkyl group mixed with ethoxyl group). Both types of surfactants exhibit very low critical micelle concentration as determined by conductance, tensiometric and fluorometric techniques. Previous works on enhanced oil recovery have used only single chain surfactants. Those single chain surfactants do not produce surface tension as low as observed in this work for double chain surfactants.

The double-chain surfactants show very remarkable tolerance of high electrolyte concentration and exhibit good stability even at temperatures as high as 60 °C. It is demonstrated that they could be used to good advantage without a cosurfactant as practiced when single chain surfactants are used. It appears that the second chain acts as a cosurfactant in each case.

The synthesis of these surfactants and their work-up are considerably less tedious and less time consuming and yet give excellent yields when compared to surfactants with very bulky headgroups. They are therefore cost effective. The surfactants with bulky headgroups were tried in order to see if they will enhance the increase in oil solubility. However, they not only show poor comparison with respect to double-chain surfactants, but are more difficult to synthesize due to steric effects.

It was shown that the double-tailed surfactants with dissimilar tail groups (one normal alkyl chain, the other containing ethoxylated groups) show remarkable ability to tolerate high soda ash concentration. The implication of this is that this type of surfactant will be very good for enhanced oil recovery in oil field with high carbonate content. This was shown in Technical Report No. 5.

On the other hand, the double-tailed surfactants with similar tail groups (linear alkyl chains) show high tolerance of sodium chloride even at high temperatures. This implies that will be very suitable for use in area of high sodium chloride content. Real crude oil from The Burbank and Ekofisk Oil fields were used to verify the observations made using hexane. In each case the conclusion that these surfactants are very good candidates for enhanced oil recovery projects were vindicated.
The rheology of both surfactants using real crude oil from sources mentioned above show a normal emulsion profile. Both show non-Newtonian behavior and thinning effect with increase in shear rate. This is particularly very good for enhanced oil recovery at moderate temperatures. The viscosity in each case were observed to be moderate that neither cosurfactant nor polymer additives will be very necessary. The efficacy of double-tailed surfactant in enhanced oil recovery projects as demonstrated in this work should encourage the use of these surfactants for further work.

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