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Effect of Oil Viscosity on Recovery Processes in Relation to Foam Flooding

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ABSTRACT

Laboratory experiments were conducted to determine the effect of oil viscosity on the oil-recovery efficiency in porous media. The pure surfactants (i.e., sodium dodecyl sulfate and various alkyl alcohols) were selected to correlate the molecular and surface properties of foaming solutions with viscosity, and the recovery of oil. Oil-displacement efficiency was measured by water, surfactant-solution and foam-flooding processes, which included 2 types of foams (i.e., air foam and steam foam). A significant increase in heavy-oil recovery was observed by steam foam flooding compared with that by air foam flooding, whereas for light oils, the steam foam and air foam produced about the same oil recovery. An attempt was made to correlate the chain-length compatibility with the surface properties of the foaming agents and oil-recovery efficiency in porous media. For mixed foaming systems ($C_{12}\ SO_4\ Na + C_n\ H_{2n+1}\ OH$), a minimum in surface tension, a maximum in surface viscosity, a minimum in bubble size and a maximum in oil recovery were observed when both components of the foaming system had the same chain length. These results were explained on the basis of thermal motions (i.e., vibrational, rotational and oscillational) and the molecular packing of surfactants at the gas-liquid interface. The effects of chain-length compatibility and the surface properties of mixed surfactants are relevant to the design of surfactant formulations for oil recovery under given reservoir conditions.

INTRODUCTION

The performance of the enhanced oil-recovery processes is expected to be governed by the properties of the displacing fluid and displaced oil and by the characteristics of the reservoir rocks. The properties of the fluids include their viscosities, flow velocities and interfacial tension at liquid-liquid interface, whereas rock properties include rock wettability, porosity and oil and water permeability of the porous media (1). After water flooding, usually $\frac{1}{2}$ to $\frac{2}{3}$ of the oil initially present in a reservoir is believed to remain in the reservoir in the form of oil ganglia trapped in the pore structure of the rock. These oil ganglia are trapped because of a very low capillary number, which is defined as the ratio of the viscous force to the capillary force (2). Moreover, in steam or gas drive processes, the high mobility and low density of the gas phase cause significant problems of channeling and gravity override. These problems lead to the early breakthrough of the gas phase at the production wells and the gas phase bypasses a considerable volume of the reservoir, which in turn reduces oil recovery. One possibility for minimizing these problems is to have a steam or gas present as foam.

Surface-active agents can be used as additives to reduce capillary forces as well as to reduce the mobility of steam or gas by in situ foaming. This, in turn, reduces channeling and gravity override. The use of foams had been proposed in the field of gas and oil production by earlier investigators (3). Foam has unique properties that are considerably different from those of its components. The viscosity of foam is higher than either of its components (i.e., gas and surfactant solution). In addition, foam is a relatively low density material that can easily overcome gravitational effects and can pass through most of the regions of a heterogeneous reservoir. A reduction in mobility and gravity override promotes oil recovery.

In recent years, foams have been used in the petroleum industry for various operations, such as fracturing, acidizing, drilling, workover, completion and mobility control, during thermal oil-recovery processes (4-12). Foams have been suggested to prevent gas leakage through the cap rock of a gas reservoir (13,14). A number of research papers have been published on foam behavior in porous media (15-24). However, the influence of oil viscosity and the molecular properties of foaming agents on oil-displacement efficiency is not well documented. Therefore, the present communication deals with the effect of oil viscosity, chain-length compatibility and surface properties of mixed foaming agents on oil-recovery processes, with special reference to foam flooding.

MATERIALS AND METHODS

Materials

Mineral oil (Kaydol) was supplied by Witco Chemical Corporation, New York, NY. Tetradecane was obtained from Phillips Petroleum Company, Bartlesville, OK. Sodium dodecyl sulfate was purchased from Aldrich Chemical Company, Milwaukee, WI. Alkyl alcohols (98% pure) were supplied by Chemical Samples Company, Columbus, OH. Deionized, distilled water was used in all experiments.

The sand used as porous medium was obtained from AGSCO Corp., Peterson, NJ. The sand packs had permeability of about 2.5 darcy and porosity of 40%. The transducer, model DP-15, used for the measurements of pressure difference across the porous medium, was purchased from Validyne Engineering Corporation, Northridge, CA. The recorder, model Heath Schlumberger 225, was obtained from Heath Company, Monton Harbor, MI. The water was pumped using cheminert metering pump model EMP-2, Laboratory Data Control, Riviera Beach, FL. The steam was produced and pumped using a laboratory steam generator, model MB-6, Automatic Steam Products Corporation, Long Island City, NY.

Methods

Surface tension. The surface tension of the freshly prepared foaming solutions was measured by the Wilhelmy plate method (25). Ca. 2 hr were allowed for equilibration of the surface. The platinum plate was always cleaned before use. All experiments were carried out at 20 ± 1 C.

Bulk and surface viscosities. The bulk viscosity of the oils was measured using either a Wells-Brookfield viscometer or a Cannon-Fenske viscometer. A single knife-edge rotational viscometer was used for measuring the surface viscosity of the foaming solutions (26). Surfactant solutions (20 mL) were poured in the cup. Ca. 10 min were allowed for equilibration of the surface. The bob was then lowered onto the solution surface by observing the meniscus at the edge of the bob. The angular deflection was measured at various speeds. The rotational speed was adjusted continuously and smoothly to the desired speed from 0-10 rpm. The bob, 4 cm in diameter, and the cup, 5 cm in diameter, were used for most of the measurements. At least 3 readings were taken for each solution. The results were reported as the average values.

Bubble size. A special type of rectangular plexiglass cell was used for the measurement of bubble size (27). Surfactant solutions (10 mL) were placed in the cell. The foams were generated by shaking a plexiglass cell by hand for 2 min. The photomicrographs of foams were taken using a camera attached to a microscope. The average size of the bubbles was determined from the size-frequency analysis of the photomicrographs.

Oil displacement in porous media. The sand packs used as porous media were flushed vertically with carbon dioxide for ca. 1 hr to displace interstitial air. Distilled water was pumped through and the volume of water retained in the porous medium (pore volume) was determined. Several pore volumes of water were injected so that the trapped gas bubbles in porous media were easily eliminated because of the solubility of carbon dioxide in water. Five pore volumes of water were pumped through at different flow rates to determine the absolute permeability of the porous medium using the darcy equation (28). After the permeability was determined, the oil of known bulk viscosity was injected in a porous medium at a constant flow rate until irreducible water saturation. This was followed by injection of water to determine the oil recovery at water breakthrough. In a separate experiment, water flooding was replaced with surfactant-solution flooding and the oil recovery at surfactant breakthrough was measured. To determine oil recovery by foam flooding, the gas or steam injection started after the breakthrough of surfactant solution to generate in situ foam. The steam was produced at a temperature of 135 C. The pressure difference across the porous medium was measured using a pressure transducer and recorder. The pressure transducer was calibrated with a sensitive pressure gauge. The oil recovery was measured at water, surfactant solution and foam breakthrough.

RESULTS AND DISCUSSION

Maximum Oil Saturation

In order to obtain different viscosity oils, a model heavy oil (Kaydol) and normal tetradecane were blended in various proportions. After water permeability was determined, the oil of known bulk viscosity was pumped in a porous medium at a constant flow rate and maximum oil saturation was measured. The effect of oil viscosity on maximum oil saturation at different injection rates is shown in Figure 1. As can be seen from the results, the maximum oil saturation increases with increasing oil viscosity. These results can be explained by considering the capillary number, which is the ratio of the viscous to capillary forces. Various expressions for the capillary number have been proposed by previous investigators (29-31). However, the modified expression by Abrams (32) only includes the influence of relative viscosities (μ_o/μ_w) on the residual saturation of displaced fluid.

Figure 1 shows that the irreducible water saturation is higher for low-viscosity oils than that for high-viscosity oils. These results suggest that the entrapment of the displaced fluid (i.e., water) depends on the viscosity ratio of the displacing fluid (i.e., oil) to displaced fluid (i.e., water). The viscosity ratio influences the relative velocities. An increase in the capillary number would improve the displacement efficiency of the displaced fluid (i.e., increase the saturation of the displacing fluid in a porous medium). These results agree with those obtained by Abrams (32).

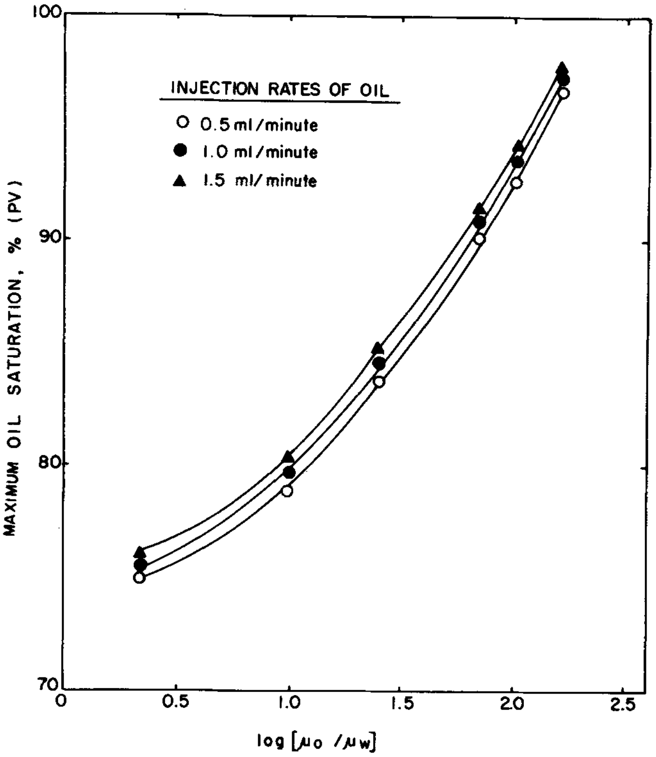


FIG. 1. Effect of oil viscosity on maximum oil saturation in sand packs of permeability 2.42 darcy and 40% porosity.

Displacement Efficiency by Water Flooding

The effect of oil viscosity on oil recovery by water flooding is shown in Figure 2. The displacement efficiency increases with decrease in oil viscosity. By reducing oil viscosity from 160 to 2 cp, ca. 35% more oil can be recovered by water flooding. Water flooding recovers 75% of light oils ($\mu_o \approx$ 2 cp) compared with 39% of heavy oils ($\mu_o \approx$ 160 cp). As the oil viscosity increases, the viscosity ratio decreases, which in turn decreases the capillary number (32). The reduction in the capillary number decreases oil-displacement efficiency (30).

The curves in Figure 2 indicate that the water breakthrough occurs between 0.30-0.46 pore volume. As the oil viscosity decreases, the oil recovered at water breakthrough increases. The data in Figure 2 are plotted in a conventional way to understand a correlation between the oil viscosity and the oil recovered at water breakthrough (Fig. 4). A linear relationship was observed between oil-recovery efficiency at water breakthrough and the logarithms of oil viscosity (Fig. 4).

Displacement Efficiency by Surfactant Solution Flooding

Figure 3 represents oil recovery by surfactant solution flooding. The addition of surfactants to the displacing fluid slightly improved oil recovery compared with recovery in the absence of surfactants (Fig. 3). The general trend in the variation of oil recovery with viscosity was the same as in water flooding. Surfactant solution flooding recovered about 77% light oils ($\mu_o \approx$ 2 cp) and 44% heavy oil ($\mu_o \approx$ 160 cp). The presence of surface active agents in the displacing fluid slightly increases the capillary number because

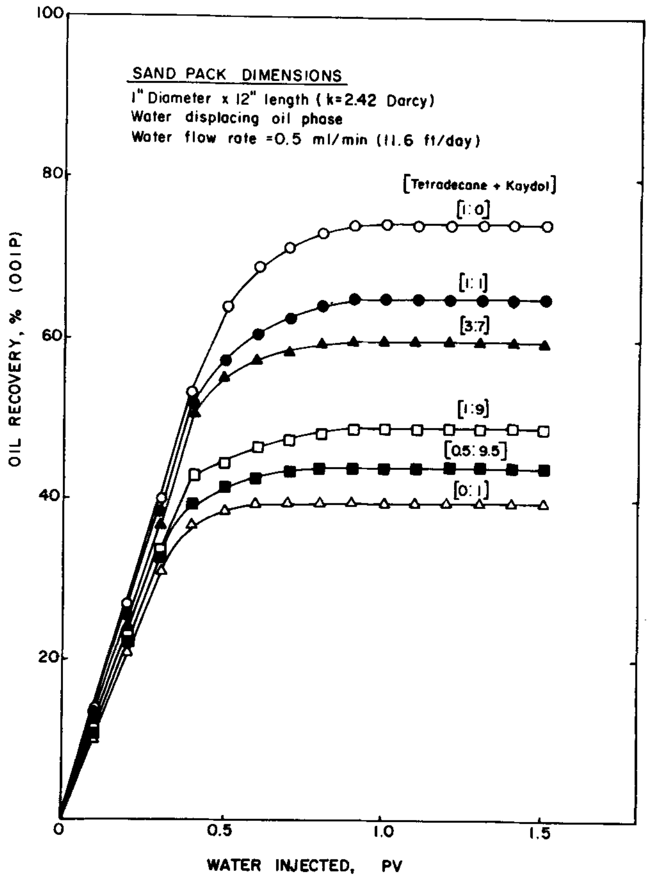


FIG. 2. Effect of oil viscosity on displacement by water flooding in sand packs. [○, 2.19 cp; ●, 10.92 cp; ▲, 24.00 cp; □, 82.41 cp; ■, 124.18 cp; △, 161.77 cp]

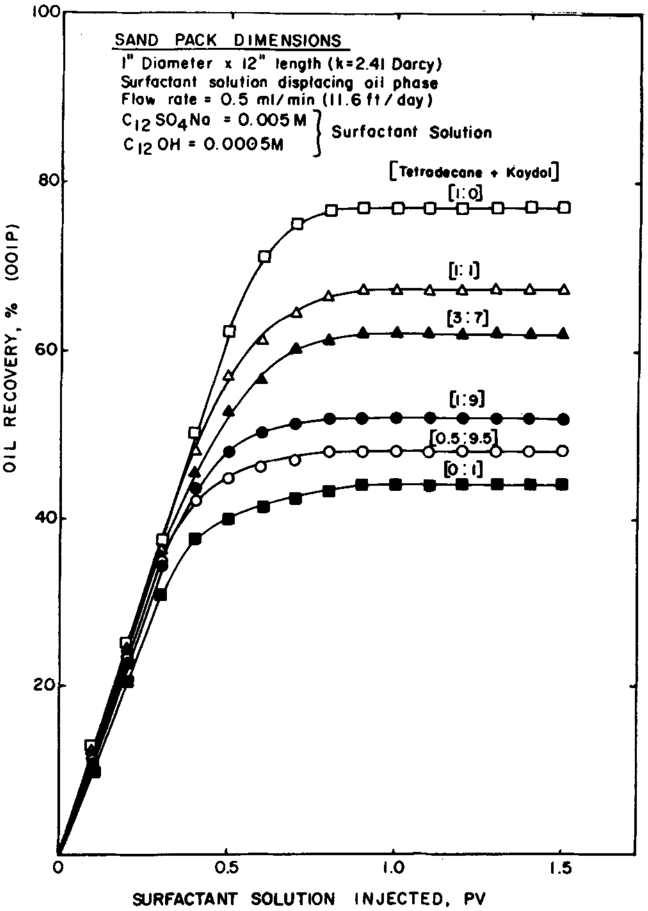


FIG. 3. Effect of oil viscosity on displacement by surfactant flooding in sand packs. [□, 2.19 cp; △, 10.92 cp; ▲, 24.00 cp; ●, 82.41 cp; ○, 124.18 cp; ■, 161.77 cp]

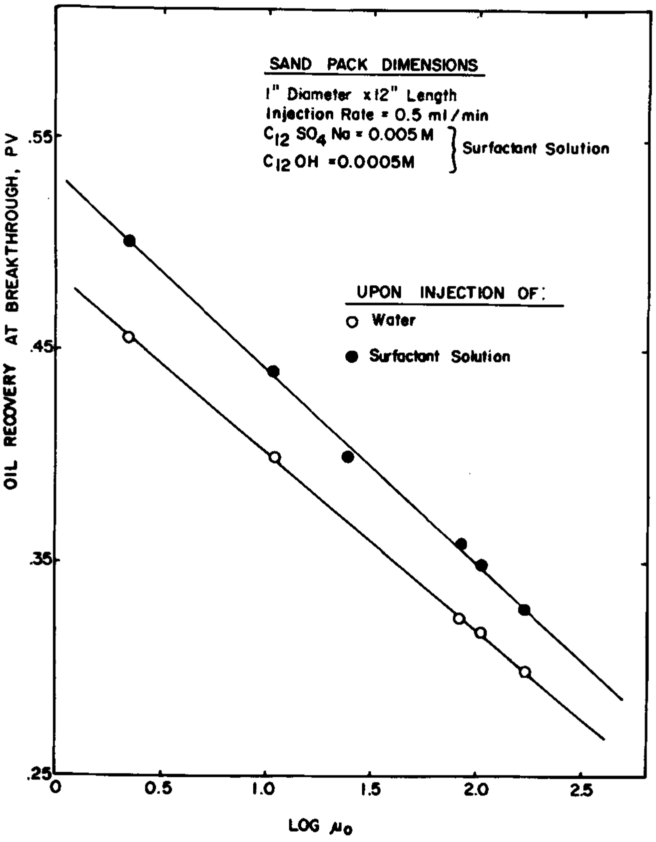


FIG. 4. Effect of oil viscosity on the oil recovery at breakthrough in sand packs.

of the reduction in interfacial tension, which in turn improves oil recovery.

The oil recovered at surfactant-solution breakthrough or water breakthrough, as a function of oil viscosity, is shown in Figure 4. Surfactant-solution flooding exhibits higher oil recovery than water flooding.

Displacement Efficiency by Foam Flooding

To determine oil recovery by foam flooding, the injection of the gas phase was started at surfactant-solution breakthrough. The gas was injected at a constant pressure of 10 psi to generate foam in the porous medium. Figure 5 shows the variation in residual oil saturation after foam flooding as a function of oil viscosity. The steam and air were used to generate in situ foams. The steam foams recovered more oil than air foams. The recovery of light oils improved slightly using steam foams compared with air foams. The effectiveness of steam foams in recovering additional oil compared with air foams increases with increasing oil viscosity. A sharp increase in residual oil saturation was observed up to 25 cp oil viscosity. Beyond this, the residual oil saturation increased gradually.

The injection of steam in porous media generates foam and reduces oil viscosity, whereas oil viscosity remains the same during air injection to generate in situ foam. Moreover, the ability to generate foam increases with increasing temperature, whereas the foam stability decreases with increasing temperature (27). The ability of the surfactants to produce in situ foam has been shown to be one of the important factors in the displacement of fluid in a porous medium. In addition, the stability of a foam is not required for efficient displacement or for a decrease in the effective gas mobility in a porous medium. The effectiveness of foam in displacing fluid in porous media and in reducing gas mobility was increased with increasing temperature (27).

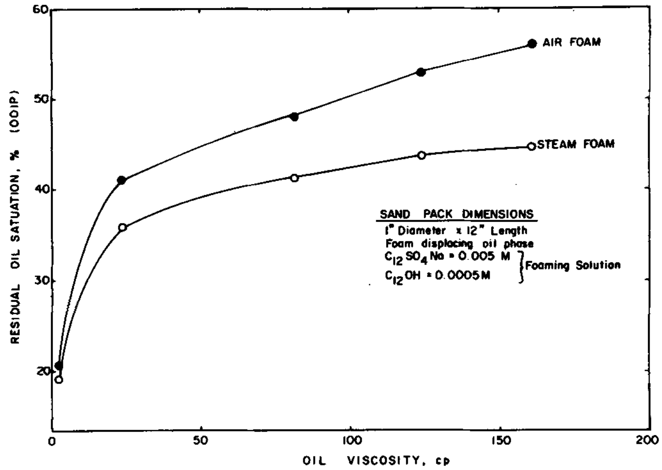


FIG. 5. Effect of oil viscosity on residual oil saturation at foam breakthrough in sand packs.

Steam injection produces more in situ foam than air injection. Therefore, the reduction in oil viscosity and the higher foaminess of the surfactants during steam injection presumably improve oil recovery in porous media. Further studies are needed to delineate the separate contribution of each factor to oil recovery. The data of oil recovery as a function of oil viscosity are presented in Table I. The oil recovery results were reproducible within ±5%.

Effect of Chain Length Compatibility and Surface Properties of Surfactants on Oil Recovery

In order to correlate the chain-length compatibility and surface properties of surfactants with oil-displacement efficiency in porous media, various alkyl alcohols (C_8-C_{16}) were mixed with sodium dodecyl sulfate in a molar ratio of 10:1 (5 mM:0.5 mM). Mineral oil (Kaydol) with a viscosity of 162 cp was used. Figure 6 illustrates the photomicrographs of various foams at 15 min intervals after the foams were generated by shaking the plexiglass cells by hand. The mixed surfactants of similar chain length produced smaller bubbles than the mixed surfactants of dissimilar chain length. An average size for the bubbles was determined from a size-frequency analysis of the photomicrographs.

The study of the surface properties of foaming agents shows that a maximum in surface viscosity and a minimum in surface tension were observed when both components of the system had the same chain length. The reduction in surface viscosity was noticed with either a decreasing or increasing chain length of alkyl alcohols from 12 carbon atoms, while surface tension increased with the increasing difference in the chain length of mixed foaming agents. The high surface viscosity presumably decreases the rate of thinning of liquid film as well as the drainage rate of liquid in bubble walls, resulting in high foam stability. Similar results on surface viscosity and foam stability were reported by previous investigators (33-35) using decanoic acid and decanol as mixed foaming agents.

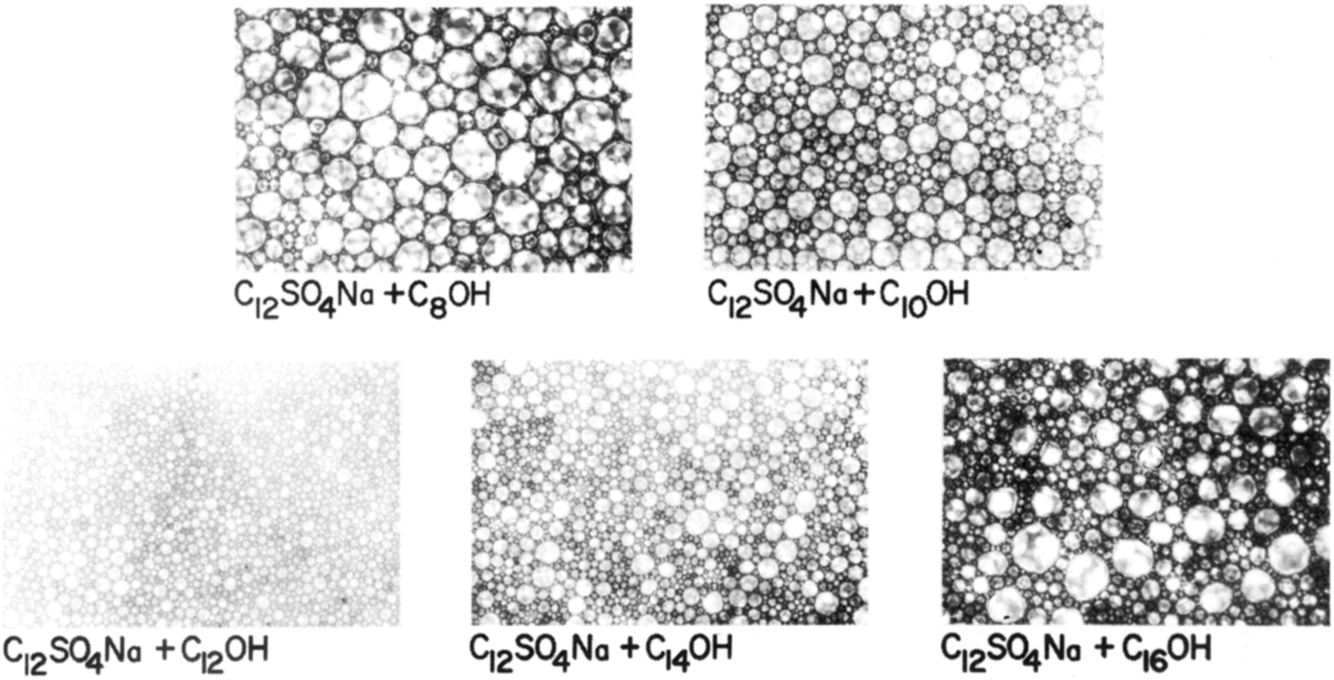
The heavy-oil recovery in porous media was measured by surfactant-solution flooding, air foam flooding and steam foam flooding processes. Figure 7 shows a correlation of the chain-length compatibility with surface tension, surface viscosity, bubble size and heavy-oil recovery efficiency at surfactant-solution breakthrough as well as at foam breakthrough. Air injection after the surfactant-solution breakthrough recovered ca. 2% additional oil. Replacing air by steam injection recovered ca. 12% additional oil. The steam injection presumably decreases the viscosity of heavy oil and generates more foam in porous media than air injection, resulting in an increase in heavy-oil recovery.

TABLE I

The Effect of Oil Viscosity on Oil Recovery at Water, Surfactant-Solution and Foam Breakthrough

S. number	Oil viscosity (cp)	Maximum oil saturation (percent)	Oil recovery (percent of original oil in place)			
			At water breakthrough	At surfactant-solution breakthrough	At foam breakthrough	
					Air foam	Steam foam
1	2.19	75.0	64.6	73.9	79.7	80.5
2	10.92	78.8	52.4	61.8	66.5	69.2
3	24.00	82.3	46.5	55.8	59.1	64.0
4	82.41	90.0	39.0	49.2	52.4	59.1
5	124.18	92.5	34.7	44.6	47.2	56.8
6	161.77	96.7	32.3	41.5	43.8	55.4

Note: Dimensions of sand pack = 1" X 12"; injection rate = 0.5 mL/min (= 11.6 ft/day).



$C_{12}SO_4Na + C_8OH$

$C_{12}SO_4Na + C_{10}OH$

$C_{12}SO_4Na + C_{12}OH$

$C_{12}SO_4Na + C_{14}OH$

$C_{12}SO_4Na + C_{16}OH$

FIG. 6. Photomicrographs of foams containing $C_{12}SO_4Na$ (0.005M) and various alkyl alcohols (0.0005M) 15-min after the foams were produced.

For mixed foaming systems, a minimum in surface tension, a maximum in surface viscosity, a minimum in bubble size and a maximum in heavy-oil recovery efficiency at surfactant-solution breakthrough, as well as foam breakthrough, were observed when both of the components of the system had a similar chain length. These results agree with those reported earlier by measuring breakthrough time and fluid displacement efficiency in sand packs and sandstones (14). We conclude that the molecules of equal chain length are packed tightly at the air-water interface. From monolayer studies (36), the intermolecular distance between molecules in mixed monolayers has been shown to be minimal for surfactants of similar chain length and increases with increasing difference in the chain length of both components of the surfactants. Our explanation for this chain-length compatibility effect, based on the concept of the thermal motion of hydrocarbon chains at the interface, was discussed in detail previously (37). The chain-length compatibility appears to play an important role in molecular packing at interfaces, which in turn influences the surface properties of the foaming agents, microscopic characteristics of foams and flow-through porous media behavior of foams. These results can be used in designing surfactant formulations for oil recovery under given reservoir conditions.

ACKNOWLEDGMENT

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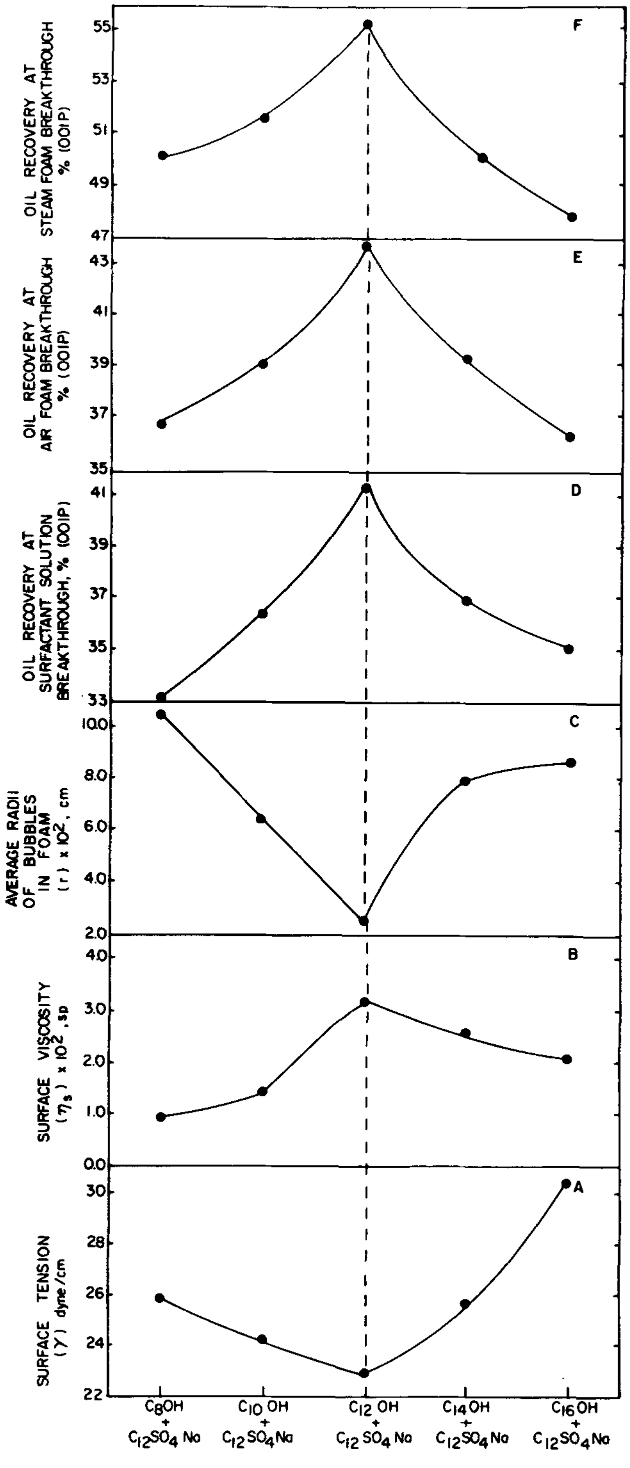

FIG. 7. A correlation of surface properties of the mixed surfactants with heavy-oil displacement in sand packs.

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