APPLICATION OF ALKALINE WATERFLOODING TO A HIGH ACIDITY CRUDE OIL

M.H. SAYYOUH
King Saud University [1]

A. ABDEL-WALY and A. OSMAN
Cairo University [2]

A.Z. AWARA
Geisum Oil Company [3]

APPLICATION DE L'INJECTION D'EAU ALCALINE AU CAS D'UN PÉTROLE BRUT A FORTE ACIDITÉ

Cet article traite de la récupération, au moyen de solutions alcalines, d'un pétrole brut à forte acidité (brut de Geisum-Sud). Différentes propriétés du pétrole brut de Geisum-Sud ont été étudiées, telles que l'acidité, la tension interfaciale et l'angle de contact. On a effectué des essais de déplacement pour étudier l'effet sur la récupération, de la concentration, de la taille et de la viscosité du bouchon alcalin ainsi que du type d'alcali utilisé et de la température.

Le pétrole brut de Geisum-Sud a un indice d'acidité élevé (4,38 mg KOH/g). On a constaté que la tension interfaciale entre le pétrole brut et l'eau et gisement diminuait lorsque la concentration alcaline augmentait pour atteindre un minimum puis qu'elle augmentait à nouveau avec l'accroissement de la concentration alcaline. La tension interfaciale entre le pétrole brut et l'eau d'injection diminue également avec l'augmentation de la concentration d'alcali. Les mesures d'angle de contact indiquent des conditions de mouillabilité à l'huile qui augmentent avec l'addition de solutions alcalines. Les expériences de déplacements montrent qu'au début du déplacement, la récupération du pétrole augmente avec l'accroissement de la concentration alcaline, pour atteindre un maximum à une concentration de NaOH de 4 % en poids. Par ailleurs, au début du déplacement, une augmentation excessive de la concentration alcaline entraîne une moindre récupération d'huile. Par contre, après l'injection de nombreux volumes de pores d'eau, la récupération est presque la même, quelle que soit la concentration alcaline injectée. On a également trouvé que l'on récupère plus d'huile lorsque la taille des bouchons de soude augmente, jusqu'à atteindre un maximum pour une taille de 15 % du volume des pores; ensuite, l'accroissement de la taille des bouchons entraîne une diminution de la récupération (ce résultat n'a pas encore paru dans la littérature). Les bouchons de soude produisent une meilleure récupération que les bouchons de carbonate de soude. Enfin, la récupération d'huile augmente avec l'accroissement de la température (de 25 à 55 °C) ou la diminution de viscosité de l'huile brute.

---

(1) Petroleum Engineering Department, College of Engineering, P.O. Box 800, Riyadh 11421, Saudi Arabia.

(2) Petroleum Engineering Department, Cairo, Egypt.

(3) Cairo, Egypt.

APPLICATION OF ALKALINE WATERFLOODING TO A HIGH ACIDITY CRUDE OIL

The main objective of this work was to study the enhanced recovery of a high acidity crude oil (South Geisum crude) by alkaline solutions. Different properties of South Geisum crude oil, namely acidity, interfacial tension, and contact angle, were investigated. Displacement tests were carried out to study the effect of alkaline slug concentration, slug size, oil alkali type, and temperature viscosity on recovery. South Geisum crude oil is a highly acidic crude (4.38 mg KOH/g). It was found that the interfacial tension between crude oil and formation water decreases with increasing alkaline concentration until it reaches a minimum, after which it increases again with a further increase in alkaline concentration. Interfacial tension between crude oil and displacement water also decreases with increasing alkaline concentration. Contact angle measurements indicated oil-wetting conditions that increase by the addition of alkaline solutions. Displacement floods showed that, at the early stages of displacement, oil recovery increases with increasing alkaline concentration until it reaches a maximum at 4 % by weight NaOH concentration. Also, at such early stages, an excessive increase in alkaline concentration results in lower oil recovery. On the other hand, after the injection of many pore volumes of water, oil recovery is almost the same regardless of the alkaline concentration. It was found also that oil recovery increases with increasing alkaline slug size until it reaches a maximum at 15 % PV, after which increasing slug size results in decreasing oil recovery (this result has not as yet been reported in the literature). Sodium hydroxide slugs produce more oil recovery than sodium carbonate slugs. Oil recovery increases with increasing temperature (from 25 to 55° C) and decreasing oil viscosity.

APLICACIÓN DE LA INYECCIÓN DE AGUA ALCALINA A UN PETRÓLEO BRUTO DE ELEVADA ACIDEZ

En el presente articulo se analiza la recuperación de un petróleo bruto de elevada acidez (bruto de Geisum-Sur), mediante soluciones alcalinas. Se examinaron diversas propiedades del petróleo bruto de Geisum-Sur, tales como la acidez, la tensión interfacial y el ángulo de contacto. También se efectuaron pruebas de desplazamiento para estudiar el efecto sobre la recuperación de la concentración, del tamaño y la viscosidad del tapón alcalino, así como del tipo de alcali utilizado y de la temperatura.
El petróleo bruto de Geisum-Sur posee un elevado índice de acidez (4,38 mg KOH/g). Se pudo comprobar que la tensión interfacial entre el petróleo bruto y el agua de yacimiento disminuía cuando la concentración alcalina aumentaba hasta llegar a un mínimo y, acto seguido, que dicha tensión aumentaba nuevamente con el incremento de la concentración alcalina. La tensión interfacial entre el petróleo bruto y el agua de inyección también disminuye con el aumento de la concentración de alcali. Las medidas de ángulo de contacto indican que las condiciones de humectabilidad respecto al aceite aumentan con la adición de soluciones alcalinas. Las pruebas de desplazamiento muestran que al comienzo del desplazamiento la recuperación del petróleo aumenta simultáneamente con el incremento de la concentración alcalina, hasta alcanzar un máximo con una concentración de NaOH de un 4 % de peso. Por otra parte, al comienzo del desplazamiento, un aumento excesivo de la concentración alcalina tiene por consecuencia una menor recuperación de aceite. En cambio, tras la inyección de numerosos volúmenes de poros de agua, la recuperación es prácticamente igual, cualquiera que sea la concentración alcalina inyectada. También se demostró que se recupera más aceite cuando el tamaño de los tapones de sosa aumenta hasta alcanzar un máximo para un tamaño del 15 % del volumen de los poros. Acto seguido, el incremento del tamaño de los poros provoca una disminución de la recuperación. (este resultado no se ha publicado aún en la literatura del género). Los tapones de sosa producen una mejor recuperación que los tapones de carbonato de sosa. Por último, la recuperación de aceite es mayor a medida que aumenta la temperatura (de 25 a 55 °C) o que disminuye la viscosidad del aceite bruto.

INTRODUCTION

Displacement of oil by alkaline solutions is an important process [1-12]. Four different mechanisms have already been proposed to explain the displacement process of oil by alkaline solutions. In all these mechanisms, reaction between the alkaline solution and various organic acids present in some crude oils results in the formation of soaps, which enhances emulsification, and the resulting emulsions either move with the flowing water stream carrying oil droplets with them or are trapped in pore throats too small to allow their movement, thus, lowering water mobility and increasing vertical and real sweep efficiency. In all cases, the interfacial tension is lowered by the emulsification process, and under some conditions, rock wettability may be altered either from oil-wet to water-wet or the reverse. This wettability change results in an increase in oil recovery regardless of the direction of wettability reversal.

The South Geisum field is an offshore field located at the southern end of the Gulf of Suez adjacent to the Red Sea, offshore from Egypt (Fig. 1). The South Geisum oil accumulation in the southern portion of the lease is in Cretaceous and Nubian sandstone and the fractured granite basement and occurs at an average depth of about 500 feet subsea. The Nubian sandstone and fractured granite basement directly underlie the Cretaceous sandstone. The reservoirs are characterized by a relatively high southward dip angle, and by heavy faulting. Average reservoir permeability is about 350 mD and reservoir temperature is 60° C.

South Geisum crude oil is highly acidic, dark black, viscous, thick, and sticky with gravities in the range of 17-24° API. This range of API values was the result of DSTs (Drill Stem Tests) at different intervals of depth and different wells.

Since the main significant characteristic of the crude oil in the South Geisum field is its high acidity (4.38 mg KOH/g), this may make the Geisum oil field a good candidate for enhanced recovery by alkaline waterflooding. Therefore, this investigation was devoted to studying the displacement of this crude by alkaline waterflooding and to investigating the effect of the concentration, size, and type of the alkaline slug as well as the effect of temperature and viscosity on oil recovery efficiency.

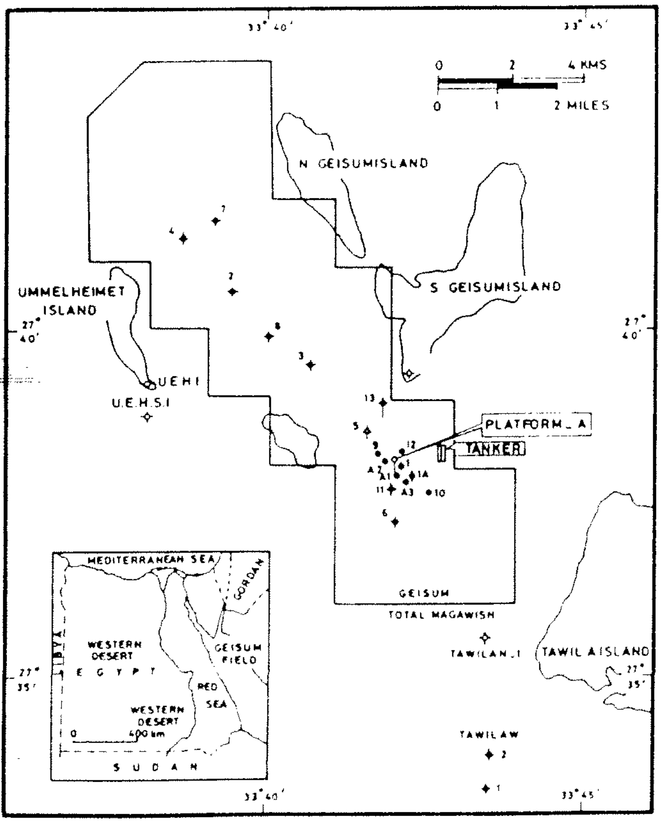


Figure 1

Location map of the Geisum concession.

EXPERIMENTAL WORK

1 Fluid properties

The acidity of Geisum crude oil was determined using the *Institute of Petroleum (IP)* procedures Nos. 1 and 182 [13]. The organic acidity was found to be about 4.38 mg KOH/g per sample of crude. The density and viscosity of the fluids used in this study are given in Table 1.

TABLE 1

Density and viscosity of liquids used

Liquid	Density (gm/cm^3)	Viscosity (cP)	Temperature (°C)
Distilled water	1.000	1.000	25
Seawater	1.027	1.020	25
Formation water	1.132	1.060	25
1% NaOH conc. in 200,000 ppm brine	1.139	1.114	25
2% NaOH conc. in 200,000 ppm brine	1.145	1.150	25
3% NaOH conc. in 200,000 ppm brine	1.152	1.186	25
4% NaOH conc. in 200,000 ppm brine	1.159	1.263	25
5% NaOH conc. in 200,000 ppm brine	1.165	1.319	25
6% NaOH conc. in 200,000 ppm brine	1.172	1.373	25
7% NaOH conc. in 200,000 ppm brine	1.179	1.450	25
10% NaOH conc. in 200,000 ppm brine	1.199	1.709	25
South Geisum crude oil	0.906	138.0	25
South Geisum crude oil	0.892	21.00	55
55% crude oil + 50% kerosine mixture	0.813	5.500	25

A complete analysis of the seawater (injected water) is given in Table 2. Also, the dissolved solids are substituted for by their equivalent NaCl ppm by using conversion multipliers.

Three water analyses were obtained for formation water. The average values for the constituents were calculated and then substituted for by their equivalent NaCl ppm by using multipliers (Ta-

TABLE 2

Seawater analysis and equivalent NaCl salinity calculations

Constituent	Salinity (mg/litre)	Multiplier	Equivalent NaCl (ppm)
Ca^{++}	701	0.95	665
Mg^{++}	1 216	2.00	2 432
Cl^-	23 412	1.00	23 412
SO_4^{--}	3 164	0.50	1 582
HCO_3^-	122	0.27	32
CO_3^{--}	36	1.26	45
Na^+	13 622	1.00	13 622
	47 550ppm Total disolved solids		41 790 Equivalent NaCl salinity

ble 3). Average salinity was found to be about 200,0 g/litre NaCl.

A Genco du Nouy tensiometer was used to determine the interfacial tension between oil and water and between oil and alkaline solution. The instrument was equipped with a temperature control system in which water with constant temperature was circulated through a glass cup jacket. Interfacial tension between South Geisum crude oil and both brine and alkaline water was measured at temperatures of both 25 and 55° C.

The contact angles that the oil droplet makes with a quartz plate in presence of brine and alkaline solutions at different temperatures were measured. The oil droplet was put in contact with the downward surface of a quartz plate under the surface of the formation water or alkaline solution in a glass container. The oil droplet was photographed at periodic time intervals (1 h.) to investigate the change of the contact angle with time until equilibrium was reached. Equilibrium time for the contact angle measurements at 25° C was about 6 h., while at 55° C this time was less than 6 h. By using a slide projection, the dimensions of the drop were measured, and the contact angle (Θ) was calculated.

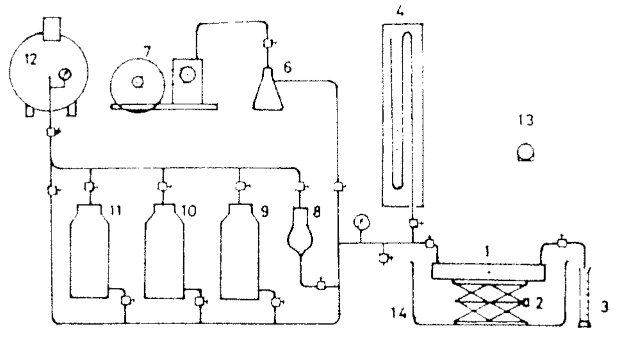
TABLE 3

Formation water analysis and equivalent NaCl salinity calculations

Constituent	Salinity (mg/litre)	Multiplier	Equivalent NaCl (ppm)
Na^+	79,311	1.00	79,311
Ca^{++}	2,295	0.95	2,180
Mg^{++}	117	2.00	234
Cl^-	116,890	1.00	116,890
HCO_3^-	574	0.27	155
SO_4^-	4,478	0.50	2,239
	203,665 Total disolved solids		201,009 Equivalent NaCl salinity

2 Displacement experiments

The apparatus used in the displacement experiments is represented schematically in Fig. 2. The model used was a quadrant of a five-spot model made from prespex which allowed visual observation. The inner dimensions of the model were 30 × 30 × 2.5 cm, and it had an injector and a producer on the two ends of the same diagonal. Screens were fixed around the bottom part of the injector and producer to prevent sand movement. A vacuum pump of the Edwards type was used to evacuate the model and connections before the start of every experiment. Four stainless-steel tanks were used for oil, formation water, displacement water and alkaline slug. An air compressor was used to provide the necessary pressure to inject any of the different liquids into the model. The pressure at the inlet of the model was measured by a pressure gauge. A water bath assembly consisting of a glass basin, electric heating coil, stirrer and an adjustable thermostat was used to control the temperature.



1 _ QUADRANT OF FIVE _ SPOT _ MODEL
2 _ MOVABLE HORIZONTAL PLATFORM
3 _ GRADUATED CYLINDER
4 _ MERCURY MANOMETER
5 _ PRESSURE GAUGE
6 _ SAND FISHER
7 _ VACUUM PUMP
8 _ SLUG RESERVOIR
9 _ OIL RESERVOIR
10 _ FORMATION WATER RESERVOIR
11 _ DISPLACEMENT WATER RESERVOIR
12 _ AIR COMPRESSOR
13 _ STOPWATCH
14 _ WATER BATH HEATER, AND ADJUSTABLE THERMOSTAT

Figure 2

Schematic diagram of the displacement apparatus.

The model was packed homogeneously with a Maadi sand mixture for which the complete mechanical analysis is given in Table 4. This sand pack had a permeability of about 5.2 D. The sand was first thoroughly washed by tap water, then by a dilute HCl solution and again by distilled water. After that it was dried in a drying oven (+ 110° C) to ensure the removal of all organic compounds if any were present. All the air was then completely evacuated from the model by the use of a vacuum pump. The model was then saturated with water having the same salinity as the field formation water. From the volume of the water used for the saturation process, the effective porosity of the sand was calculated. In all sets of displacement experiments, the effective porosity of the sand packs was in the range of 0.34. Absolute permeability was obtained by circulating formation water through the sand pack and measuring the flow rate of water at a given pressure drop across the sand pack. The model was then saturated with oil by the continuous injection of oil until the water cut in the effluent was less than 1%.

TABLE 4

Mechanical analysis of the Maadi sand used(1)

Mesh diameter	Wt. of the sand retained on the sieve (gm)	Wt. % of the sand retained	Cumulative (Wt. %)
0.630	34.5	4.00	4.00
0.500	106.0	12.26	16.26
0.400	230.0	26.62	42.88
0.315	235.0	27.20	70.08
0.250	100.0	11.57	81.65
0.200	60.0	6.94	88.59
0.160	64.0	7.52	96.11
0.125	24.0	2.78	98.89
<0.125	9.5	1.10	100.00

(1) Does not contain any clay.

At this moment, the initial saturation conditions of the reservoir were supposed to be achieved, and the alkaline slug was injected into the sand pack, followed by continuous injection of seawater for about four pore volumes. The liquids produced were collected continuously, and the amounts of oil and water in the sample were determined. It was noted that the proportion of emulsified oil was great and very difficult to break up unless an emulsion-breaker chemical was added to the effluent sample and heated.

RESULTS AND DISCUSSION

All displacement floods were carried out under the same conditions of porosity and permeability. All chemical solutions were freshly prepared just before being used to avoid any effect of precipitation. All displacement data were the average of at least two runs having good reproducibility. The average value of irreducible water saturation before injecting the alkaline slugs was 13.4%.

Effect of alkaline (NaOH) concentration on oil recovery

Figure 3 shows the cumulative oil recovery and oil cut in the samples produced versus pore volumes of water injected using 15% pore volume (PV) slug size with different $NaOH$ concentrations at a temperature of 25° C. The effect of alkaline $NaOH$ concentration on oil recovery at different displacement-water pore volumes injected is shown in Fig. 4.

It can be seen from these experiments that alkaline waterfloods recover more oil than conventional waterfloods. This increase in ultimate oil recovery is evidenced by the production of a large oil-water bank or by delayed oil production. Since South Geisum crude oil has a high acid number (4.38 mg KOH/g), the effect of alkali on oil recovery is due to the chemical reactions betwen alkali and organic acids occurring in the crude oil. These reactions result in the formation of surface-active materials (soaps) whose adsorption on the oil-water interfaces decreases the interfacial tension between oil and water, thus yeilding an oil-water emulsion. This emulsion formed can be entrained into the alkaline flow to be produced, or entrapped again, resulting in better sweep efficiency. The entrainment or entrapment of the emulsions formed depends on the interfacial tension and on the pressure gradient applied during the displacement process.

The effect of alkali ($NaOH$) on the interfacial tension between crude oil and alkaline solutions is demonstrated by interfacial tension measurements for which the results are shown in Fig. 5, which shows the interfacial tension between South Geisum crude oil and $NaOH$ solutions with

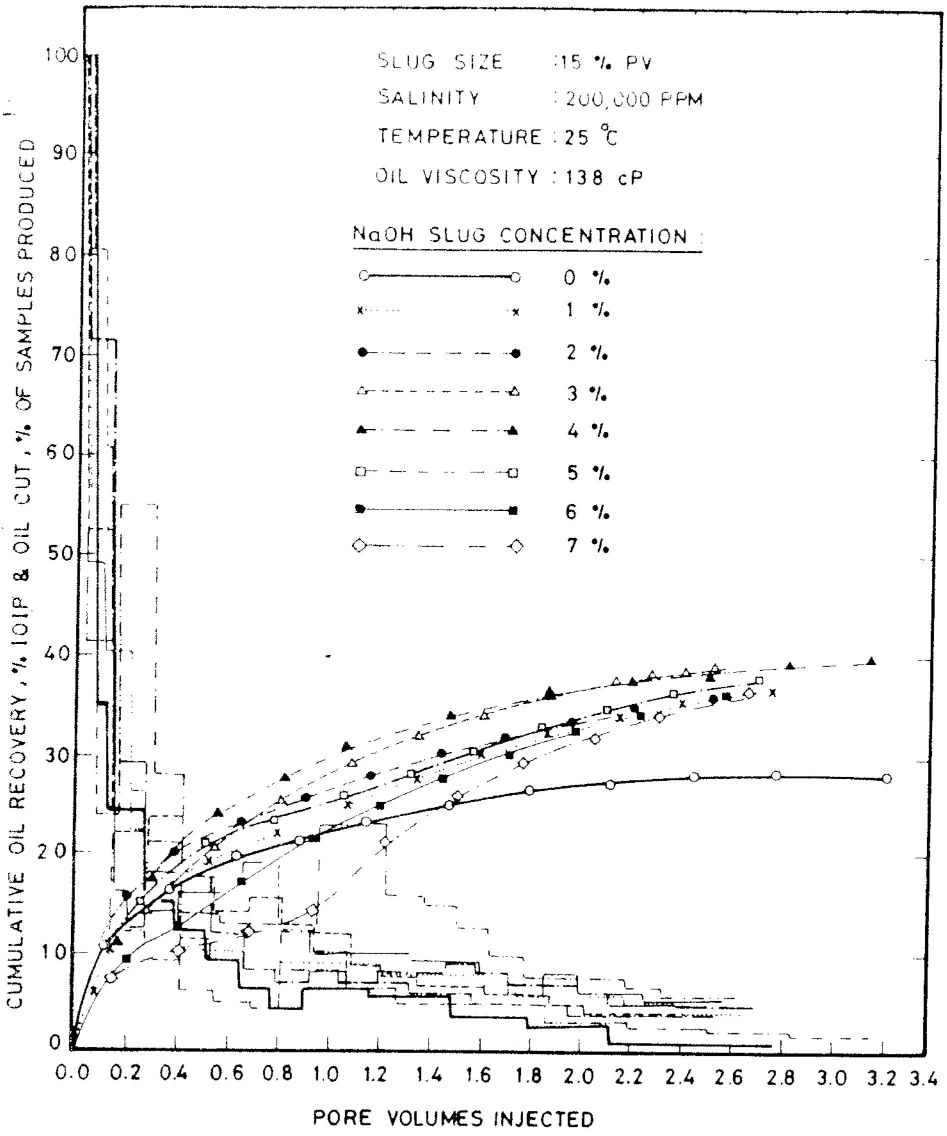


Figure 3
Effect of NaOH slug concentration on oil recovery by alkaline waterflooding.

200,000 ppm NaCl salinity versus NaOH concentration at a temperature of 25° C.

It was found that increasing the NaOH concentration decreased the interfacial tension until it reached the least interfacial tension region at 3 to 4 weight % of NaOH concentration. Further increase in NaOH concentration resulted in an increase of the interfacial tension again.

Results of contact angle measurements are shown in Fig. 6 using different NaOH solution concentrations in 200,000 and 40,000 ppm NaCl brine at a temperature of 25° C.

It was also found out from the same figure that the contact angle was affected by the alkaline concentration in such a way that the presence of 0.5 weight % of NaOH resulted in an abrupt increase in the contact angle. The contact angle increased from 127 to 172° at 0.5% NaOH concentration. Increasing the NaOH concentration kept the contact angle at the same high value range (above 170°) until the concentration reached 3 % NaOH, after which further an increase in NaOH concentration resulted in a decrease in the contact angle to 160° at 4% NaOH and to 145° at 10% NaOH concentration.

From Figs. 3 and 4, it is clear that, at the early

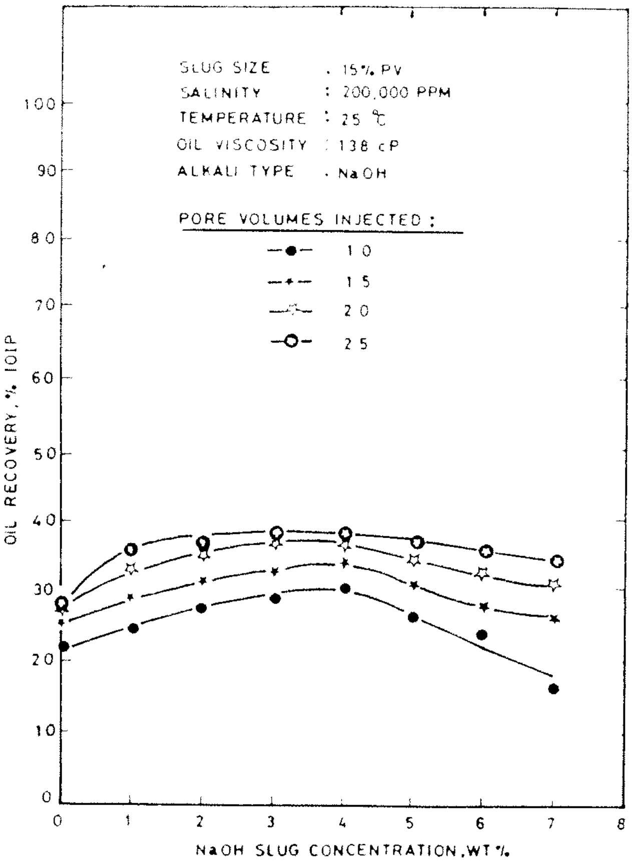


Figure 4

Effect of slug concentration on oil recovery at different pore volumes of displacement water injected.

stages of alkaline waterflooding, oil recovery increases with increasing NaOH concentration until it reaches a maximum at 4% NaOH concentration. Alkaline concentrations higher than 4% NaOH result in lowering the oil recovery to a level even below that of plain waterflooding. On the other hand, although oil recovery during early stages for higher NaOH concentrations is slow, the continuation of displacement by water injection results in a production of an oil-water bank which compensates for the early low oil recovery and which gives a comparable ultimate oil recovery at high and low alkaline slug concentrations. This leads to the conclusion that, at large numbers of pore volumes of water injected, no change in ultimate oil recovery is obtained as a result of varying alkaline slug concentrations. This behavior is clear from Fig. 4 where the oil recovery at 2.5 pore volumes injected versus NaOH concentration is almost a horizontal line after 1% NaOH concentration.

For the NaOH slug concentrations tested, the most attractive performance is that in which a 4 weight % NaOH concentration slug is used. This concentration gives the highest oil recovery at water breakthrough and a large oil-water bank at the lower water-oil ratio, which is produced during the early stages.

This result does not correlate directly with the interfacial tension measurements and hence to the adhesion tension shown in Fig. 7. This behavior can be explained by considering the reduction of the concentration of the alkaline slug inside the porous medium due to mixing with connate and displacement water and to the adsorption of alkali on the grain surfaces. As shown in Fig. 3 at the early stages of injection, higher concentration displacement floods are characterized by lower oil production, even below those resulting from conventional waterflooding. After these early injection stages, delayed oil-water banks are produced. This low early production can be attributed to the unfavorable displacement conditions present at these concentrations as a result of the high interfacial tension. The delayed oil-water bank production is due to a dilution of the NaOH slug concentration resulting from mixing with connate water in the front of the bank and from mixing with displacement water in the rear of the bank as well as to adsorption on the grain surfaces. This reduction in slug concentration leads the slug concentration to be, after some time (depending on the initial concentration), equal to or close to the favorable NaOH concentration which gives the lowest interfacial tension between oil and alkaline solution and then to produce the oil-water emulsion which will be able to be entrained in the alkaline flow to be produced. This explanation is supported by the presence of the time lags necessary for the production of the oil-water bank at these higher concentration floods. This time lag increases as the difference between the initial injection slug concentration and the favorable NaOH slug concentration increases.

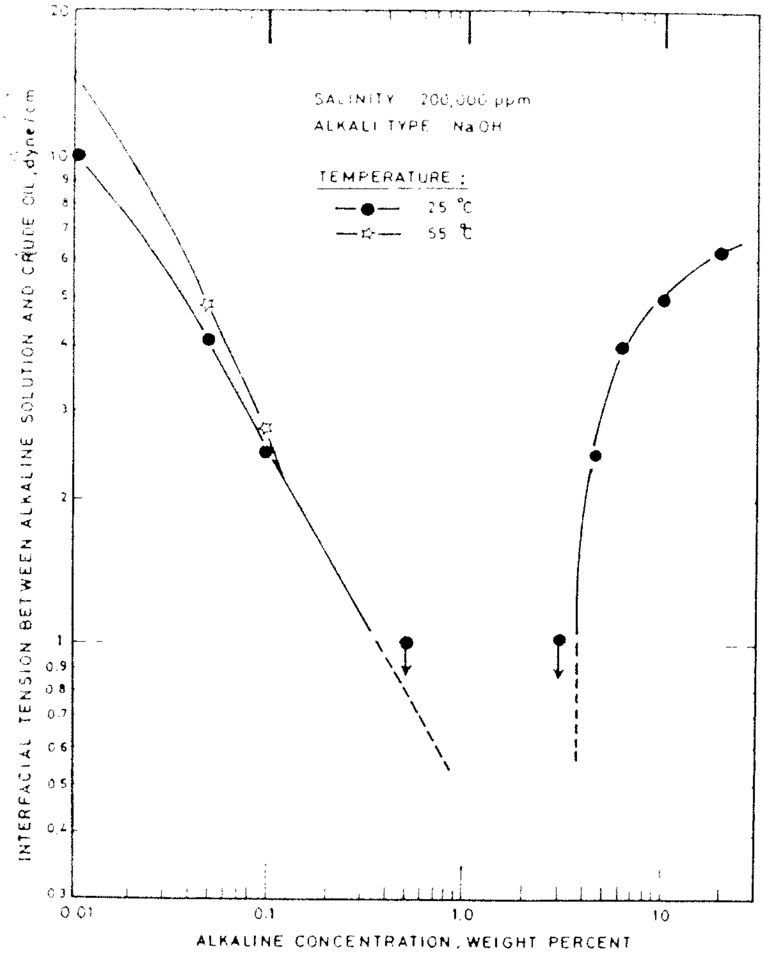


Figure 5

Interfacial tension between South Geisum crude oil and NaOH solution as a function of NaOH concentration and temperature.

Effect of slug size

Figure 8 shows the production histories for the 0, 15, 25 and 30 % pore-volume alkaline slug displacement at a temperature of 25° C. Cumulative oil recovery is expressed as a percentage of the initial oil in place. This figure shows the behavior of the oil-water bank for varying alkaline slug sizes using a 4 weight % NaOH concentration. Fig. 9 is a plot of the oil recovery versus slug size at different pore volumes of displacement water injected.

It is evident that South Geisum crude oil recovery increases with an increase in the slug size up to 15% PV, then the oil recovery decreases with the further increase in the slug size. For example, for a conventional waterflood, oil recovery was 25% of the initial oil in place at 1.5 pore volumes injected, whereas for 30% PV slug size recovery was reduced to 16% for the same pore volumes injected. This effect has not been reported in the literature by previous investigators.

The following discussion is an effort to systematically examine the effect of alkaline slug size on the mechanism of displacement of South Geisum crude oil by alkaline slug driven by brine. In general, during the initial time period, only oil is produced. After breakthrough, a stabilized oil-water bank propagates through the porous medium. Both oil and water start at a certain ratio at the oil bank breakthrough. The fluctuations observed in this ratio may be due to either the wetting properties of the rock-fluid system, the interfacial tension between liquids, the viscosity of the liquids, or the composition of the crude oil (acidity). Fig. 8 shows the behavior of the oil-

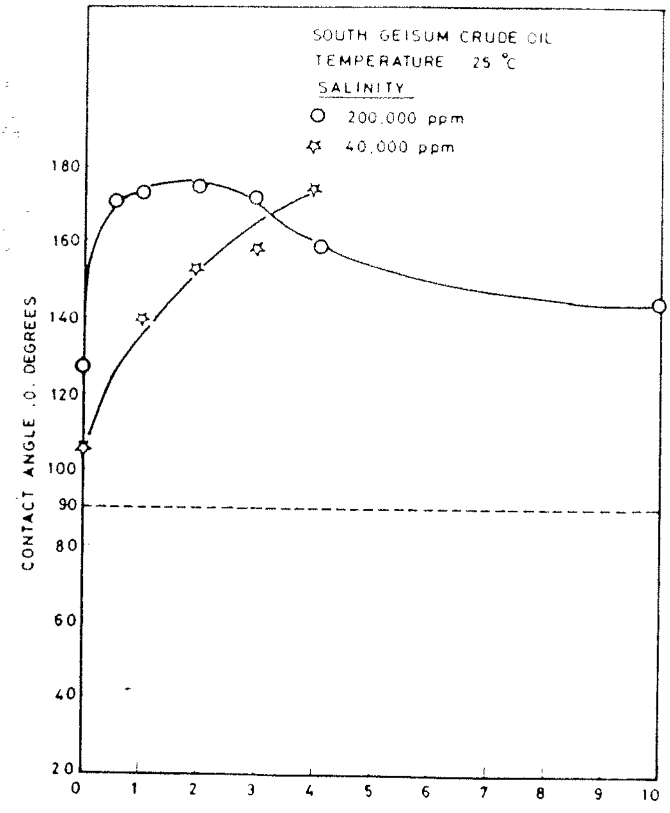


Figure 6

Contact angle as a function of alkaline concentration and salinity.

water bank for a varying alkaline slug sizes with a concentration of 4 weight % of NaOH. The distinct feature in this figure is that the oil-water bank was large when 15% PV slug size was used, and hence more recovery was obtained. It is seen from the production histories that there is a wider bank with 15% PV slug size, compared to that of either 25 or 30% PV slug size.

The increased recovery with increasing slug size up to the optimum slug size of 15% PV can be explained by a better coverage (i.e. volumetric sweep) of the displacement by alkaline water. This coverage increases with an increase in the slug size injected. A sufficient slug size is also required to ensure production of the alkaline emulsion before it is retrapped again. The problem that still arises is a decrease of oil recovery with a further increase in slug size. To explain this effect, it is necessary to consider both the alkaline concentration and salinity effects on recovery mechanisms. Reduction of caustic concentration depends on the initial slug concentration injected, which was a variable parameter during the examination of the effect of the caustic concentration. The reduction of salinity was neglected because of the constant percent of slug size. When variable slug sizes are used, it is necessary to consider the effect of the NaCl concentration change on the displacement process.

Figure 10 shows the interfacial tension between crude oil and water at two different salinity levels, namely 40,000 and 200,000 ppm NaCl (displacement seawater and slug salinities respectively). It

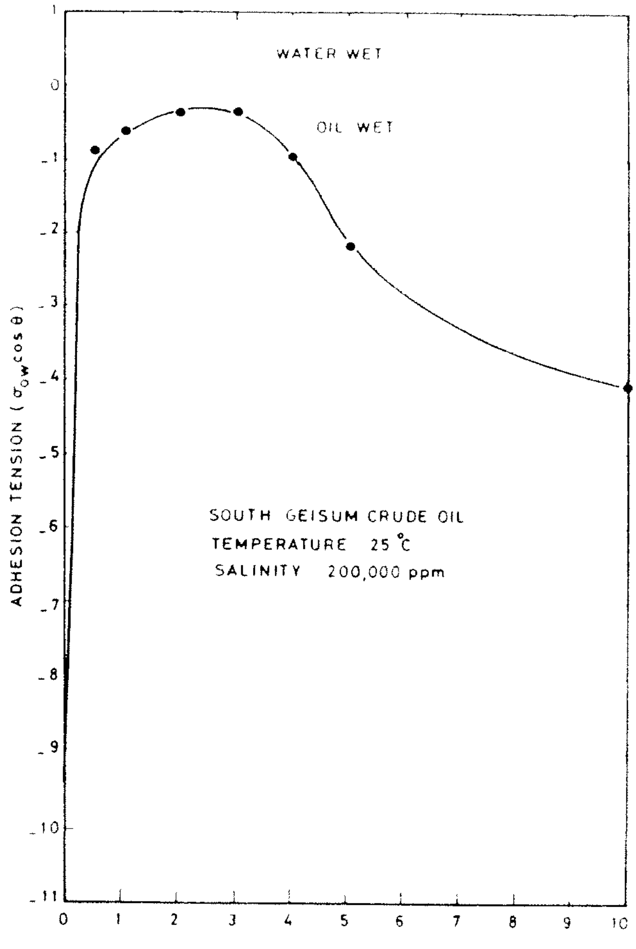


Figure 7

Adhesion tension ($\sigma_{ow}\cos\theta$) versus NaOH concentration.

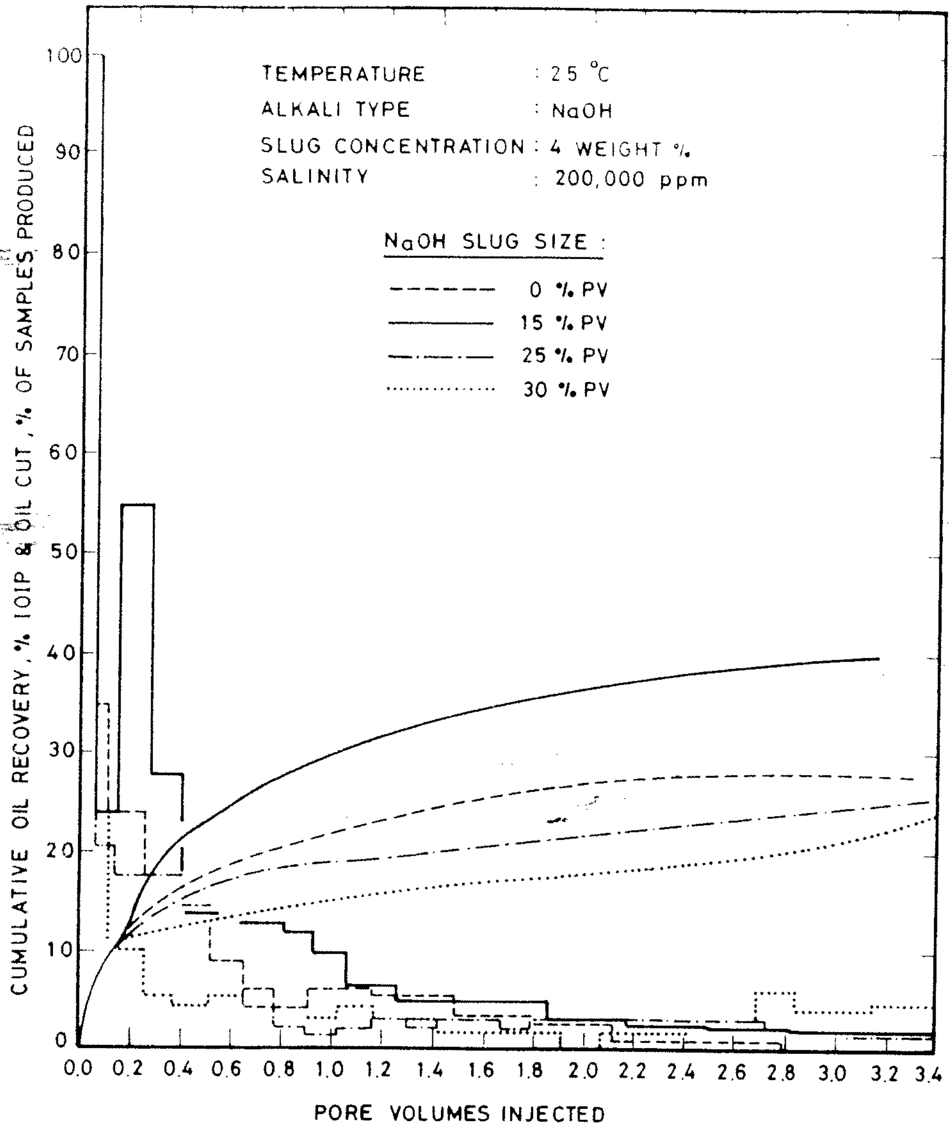


Figure 8
Effect of alkaline slug size on oil recovery by alkaline waterflooding.

is clear that the interfacial tension decreases with an increase in the NaCl concentration.

The salinity effect on both interfacial tension and contact angle can be attributed to its effect on the solubility of the surface-active materials resulting from the chemical reaction between alkaline and organic acids in the crude oil. Increasing the salinity prevents these surface-active materials from being dissolved in the water phase, causing it to be adsorbed on either the mineral surface of the rock or the oil water interface, thus enhancing oil-wetting or decreasing the oil-water interfacial tension respectively. The prevention of the surface-active materials from dissolution in water also affects the type of the oil-water emulsion formed. At higher salinities, the emulsion formed could be a water-in-oil emulsion, which is different from an oil-in-water emulsion in that it needs a higher pressure gradient to move [7, 12]. This mechanism can increase the oil recovery only if the interfacial tension is very low. This too low interfacial tension results in a lowering of the capillary forces to a sufficient degree to let them be overcome by the pressure gradient. But to have this minimum interfacial tension, caustic concentration must be at a favorable level, which corres-

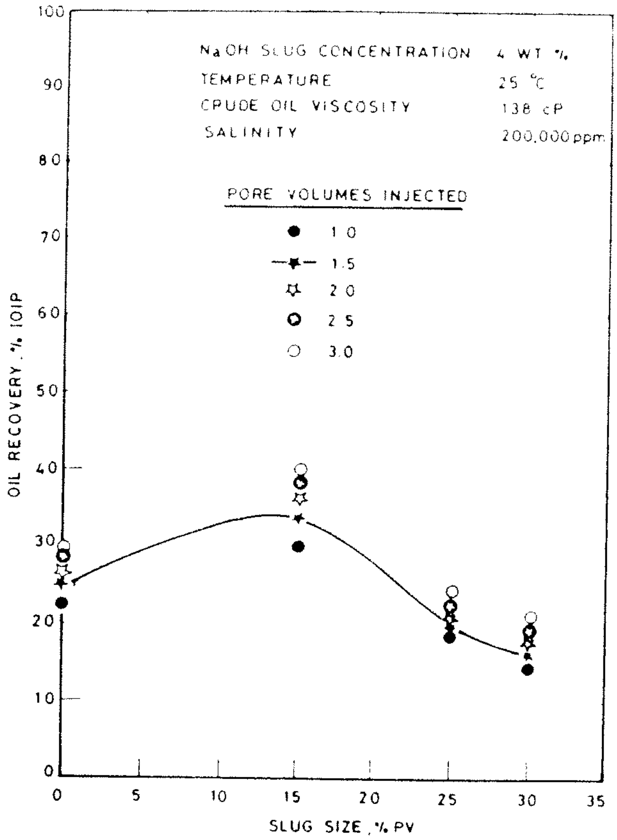


Figure 9

Effect of alkaline slug size on oil recovery by alkaline waterflooding at different pore volumes of displacement water injected.

ponds to 4% NaOH concentration at 15% PV. This caustic concentration can be achieved in the porous medium only if the concentration reduction rates are adjusted. It is expected that a slug size of 30% PV could increase oil recovery only if the concentration reduction rate is adjusted to the alkaline concentration and the salinity to provide the optimum conditions for the interfacial tension lowering. The low values of oil recovery obtained after 15% slug size may also be explained by the variation in the ratio between the quantity of alkali injected and quantity of alkali required to neutralize the oil initially in place.

Effect of alkali type

In order to compare the effects of NaOH and Na_2CO_3 alkalis on oil recovery and displacement efficiency, two floods were carried out at the same conditions of temperature of 25° C and the same slug size of 15% PV.

Figure 11 shows the cumulative oil recovery and production histories of these alkaline waterfloods. It can be seen from this figure that less oil recovery was obtained when using Na_2CO_3. The Na_2CO_3 solution of weight % concentration has a pH value of 9.77, while the pH value of the NaOH solution of the same concentration and salinity is 11.35. This difference in pH value may explain the decrease of oil recovery when Na_2CO_3 is used.

Figure 12 shows the oil-water interfacial tension versus Na_2CO_3 concentration. It is clear from this figure that interfacial tension decreases with Na_2CO_3 concentration. A comparison between the

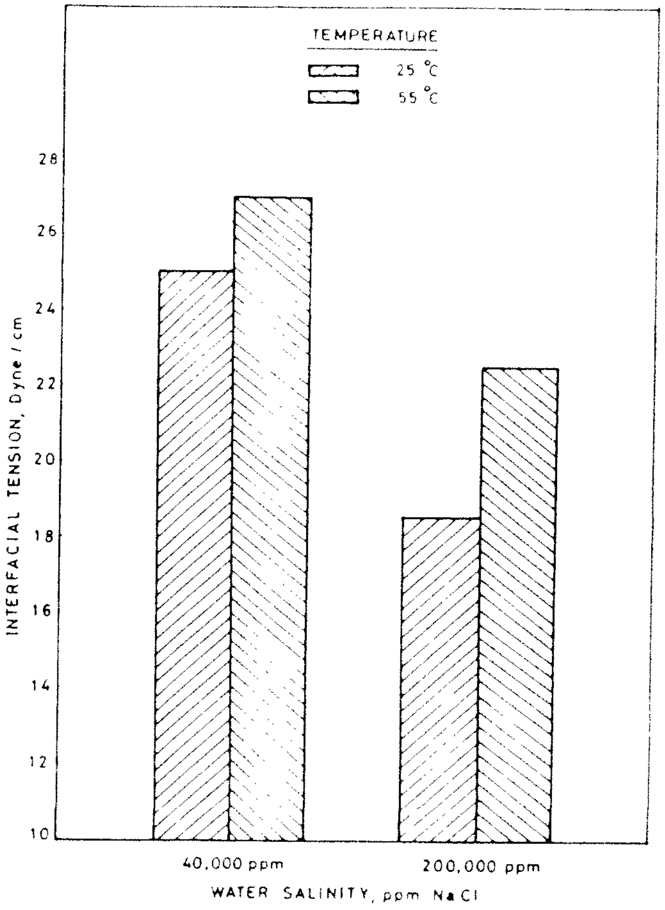


Figure 10

Interfacial tension between South Geisum crude oil and seawater and formation water.

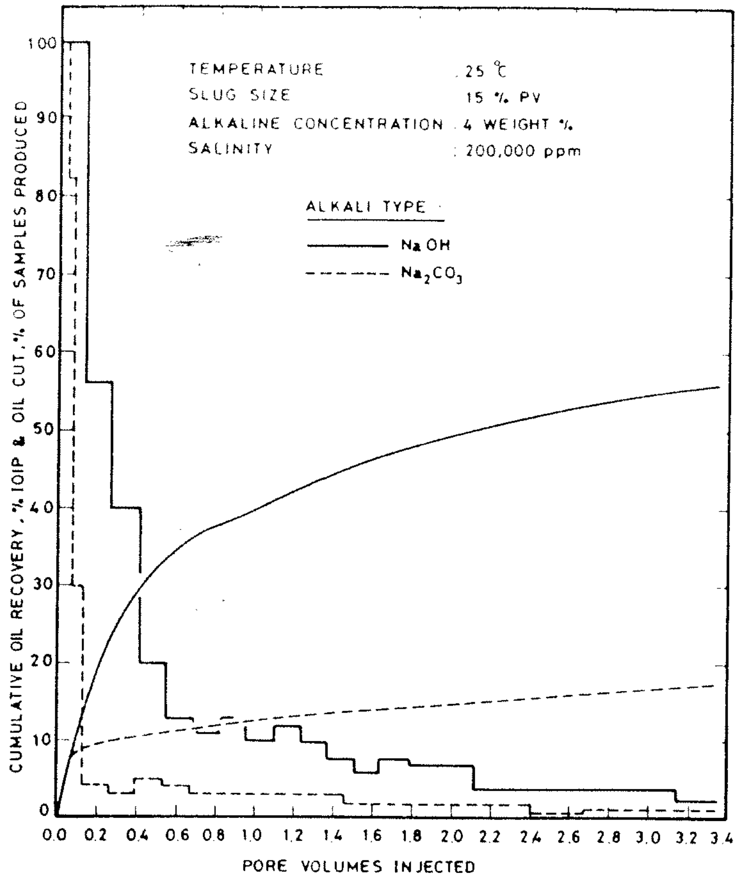


Figure 11
Effect of alkali type on oil recovery.

interfacial tension between South Geisum crude oil and both NaOH and Na_2CO_3 solutions is also shown in this figure. It is clear that the interfacial tension curves are almost the same when using either NaOH or Na_2CO_3.

As is known from the literature, the solid-water interfacial tension depends on the pH value. Since, under the present experimental conditions, the solid-oil interfacial tension has a constant value and the oil-water interfacial tension was nearly the same whether NaOH or Na_2CO_3 was used (as shown in Fig. 12), the solid-water interfacial tensions was altered by a change of the pH value of the solution used, and as a result of this variation a different oil recovery was obtained in each ease.

Effect of temperature on the displacement process

In general, temperature plays an important role in alkaline waterflooding. It affects the interfacial tension and wettability properties of the liquid-rock systems. It also affects, to a great extent, the viscosity of the fluids in the porous medium, leading to remarkable changes in the mobility control of the process and hence in oil recovery.

Figure 13 shows the production histories of two alkaline waterfloods under the same conditions of 4 weight % NaOH concentration and 15% PV slug size but at two different temperature levels of 25° C and 55° C respectively. In order to cancel out the effect of oil expansion on the recovery mechanism as a result of increasing the temperature, the formation water waturation process as well as the oil saturation one were carried out at

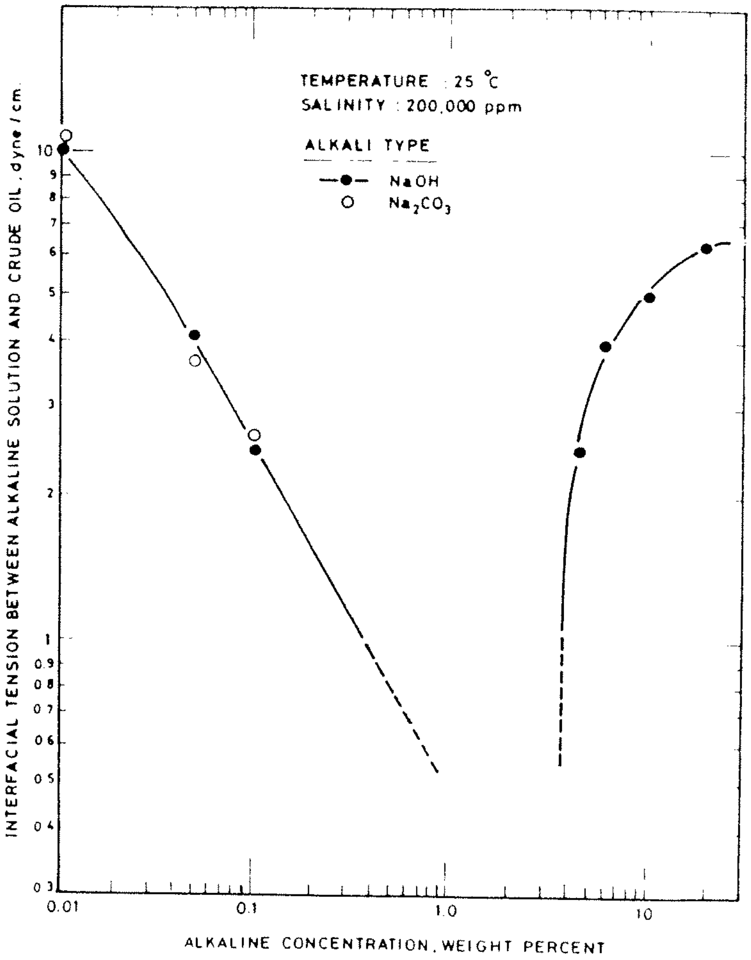


Figure 12

Interfacial tension between South Geisum crude oil and alkaline solutions (NaOH and Na_2CO_3) versus alkaline concentration.

the same temperature. Also, the recovery calculations were based on the oil produced at the same temperature.

It can be seen from Fig. 13 that a great increase in oil recovery was obtained when temperature increased from 25 to 55° C.

To explain the effect of temperature on South Geisum crude oil displacement efficiency, the contact angle and interfacial tension were measured at 55° C temperature. As shown in Fig. 14 no great change in the contact angle was observed as a result of increasing the temperature. From Fig. 5 showing the interfacial tension between oil and alkaline solutions at both 25° C and 55° C, it can be seen that interfacial tension increases slightly with increasing temperature. Therefore, it can be said that the increase in oil recovery at the higher temperature of 55° C is a result of the better mobility ratio between oil and displacement water due to decreasing oil viscosity.

This result indicates that the alkaline waterfloods carried out at the ambient temperature of 25° C are comparable and can be generalized at a higher temperature of 55° C with only a difference due to mobility ratio change.

Effect of oil viscosity

In order to further investigate the effect of the mobility ratio on the displacement efficiency, South Geisum crude oil viscosity was adjusted to a lower viscosity of 5.5 cP by mixing the crude oil with kerosene at a 50% ratio.

Figure 15 represents the production history for South Geisum crude oil (138 cP) and Geisum

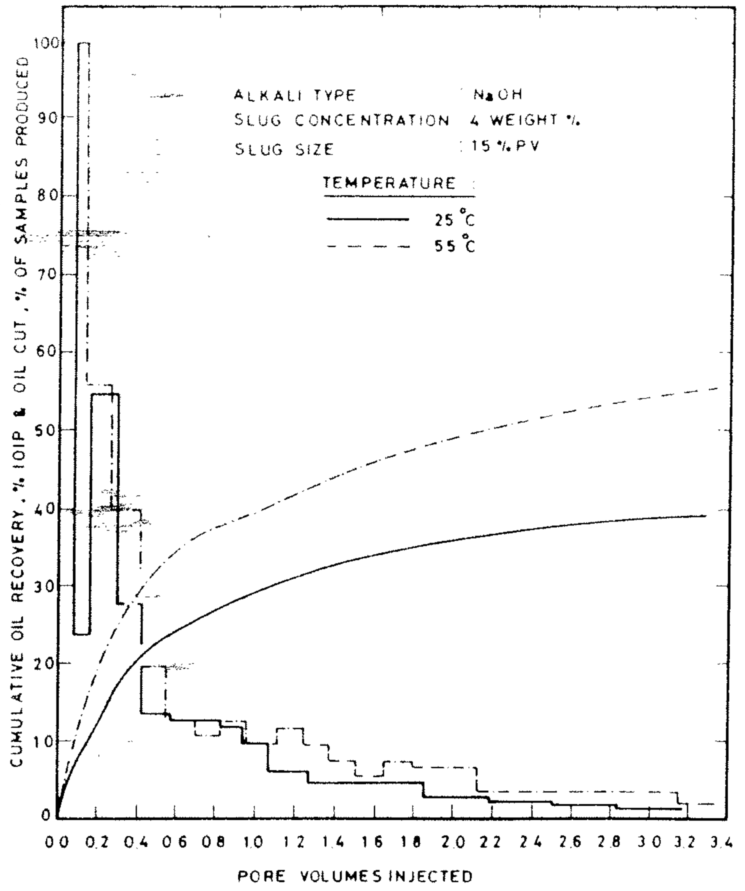


Figure 13

Effect of temperature on oil recovery by alkaline waterflooding.

crude mixed with kerosine (5.5 cP) at the same temperature of 25° C. This figure shows that oil recovery increases with decreasing crude viscosity (i.e. decreasing mobility ratio). For example, at 1.0 PV injected, oil recovery with the high viscosity flood was 22% of the initial oil-in-place, while with the low viscosity flood the recovery was 65% of the initial oil-in-place. The water-oil relative permeability is much higher when high viscosity crude oil is used, and hence lower displacement efficiency was obtained.

Figure 16 shows the production history of alkaline water displacement runs with 1% NaOH slug concentration and 15% PV slug size using South Geisum crude oil (138 cP) and oil-kerosine mixture (5.5 cP) respectively. Oil recovery increases with decreasing crude oil viscosity. On the other hand, from production history, it is noticeable that, after 1 PV of displacement water injected, the water-oil ratio is higher when low viscosity crude is used than for the high viscosity flood.

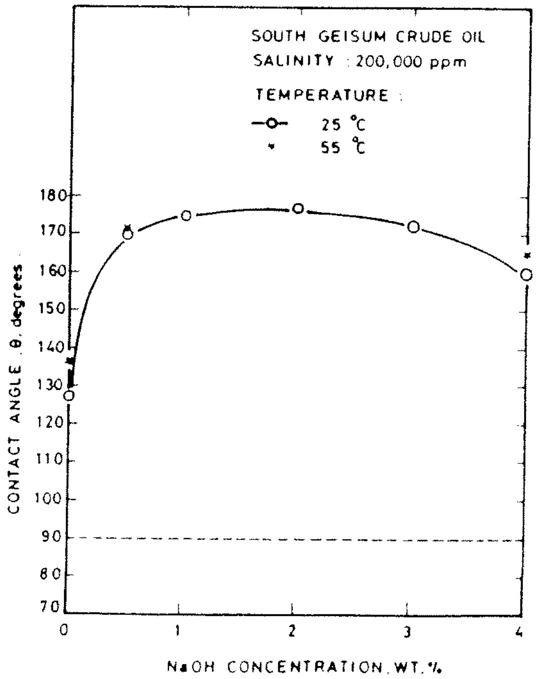


Figure 14

Effect of temperature on contact angle.

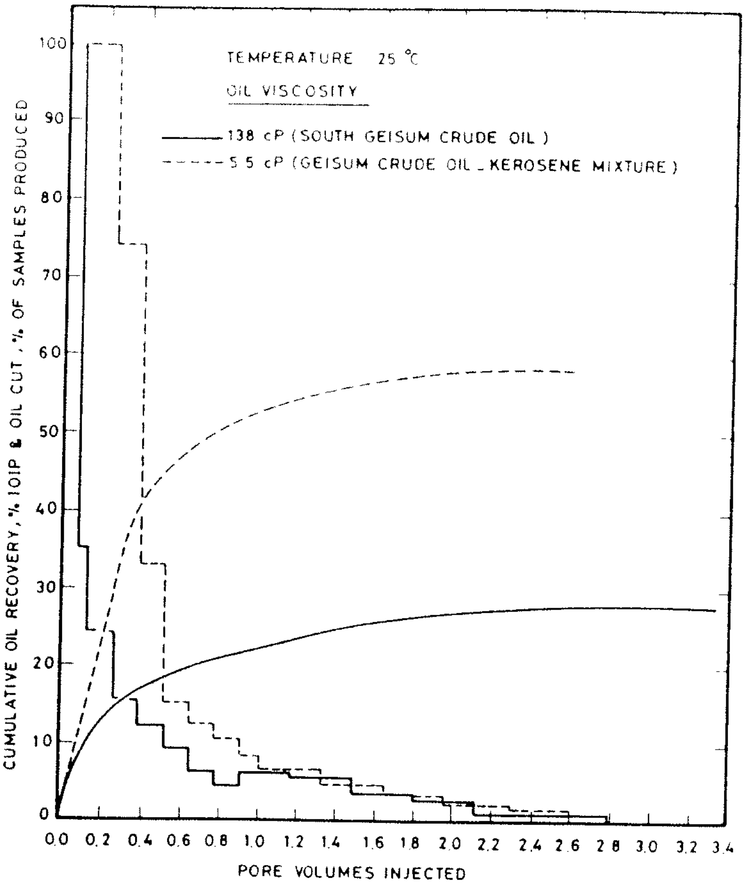


Figure 15
Effect of oil viscosity on oil recovery by conventional waterflooding.

This can be attributed to the difference in interfacial tension between the alkaline solution and both crude oil and crude-kerosine mixture.

CONCLUSIONS

The following conclusions were derived from this work:

- Interfacial tension between South Geisum crude oil (highly acidic) and alkaline (NaOH) solutions of formation water salinity at 25° C temperature decreases with increasing NaOH concentration until it reaches a minimum at 3.5-4 weight % NaOH concentration, after which it increases again with a further increase in the alkali concentration.
- Contact angle measurements under the conditions of formation water salinity and a temperature of 25° C indicated a preferentially oil-wet system
- Alkaline NaOH waterfloods recover more oil than a conventional waterflood. This increase in ultimate oil recovery is evidenced by either production of a large oil-water bank or delayed oil production.
- At early stages of displacement, oil recovery increases with increasing NaOH slug concentration until it reaches a maximum at 4 weight % NaOH. Also, at such early stages, an excessive increase in NaOH concentration results in lower oil recovery. On the other hand, after injection of many pore volumes of displacement water, oil recovery is almost the same regardless of the NaOH concentration.
- At 4 weight % NaOH slug concentration and 25° C temperature, oil recovery increases with increasing NaOH slug size until it reaches a maximum at 15% PV, after which a further increase in slug size results in decreasing oil recovery.
- At conditions of 15% PV slug size, 4 weight % slug concentration and 25° C temperature, sodium

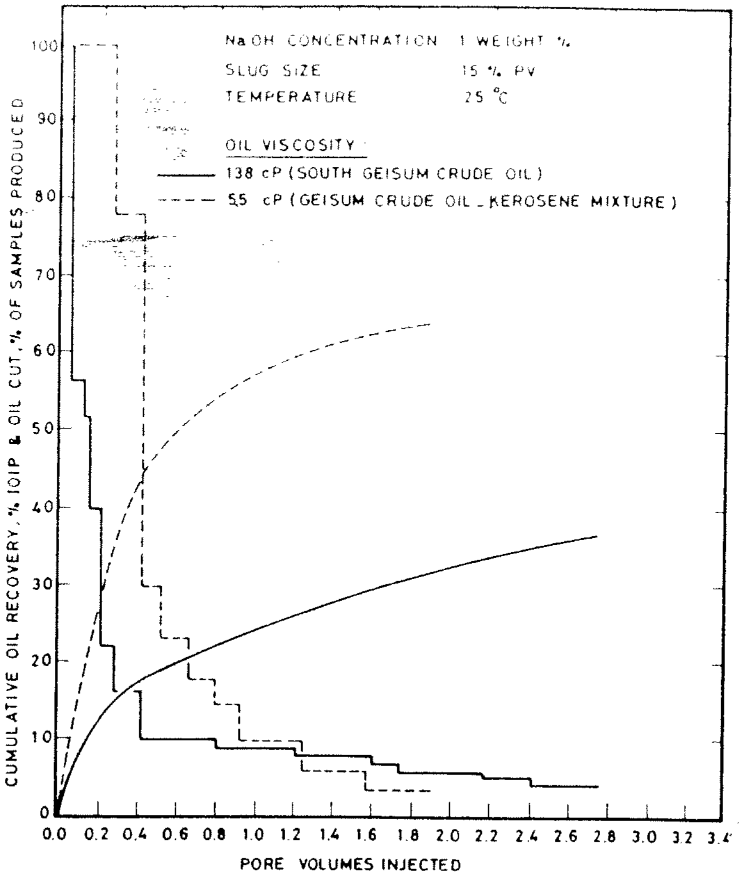


Figure 16
Effect of oil viscosity on oil recovery by alkaline waterflooding.

hydroxide slug produces more oil recovery than a sodium carbonate slug.

- Other conditions being the same, oil recovery increases with increasing temperature and with decreasing oil viscosity.

REFERENCES

1 Johnson, C.W., "Status of Caustic and Emulsion Method", *J. Pet. Tech.*, 85-92 (Jan. 1976).

2 Jennings, H.Y., Johnson, C.E., McAuliffe, C.D., « A Caustic Water-flooding Process for Heavy Oils », *J. Pet. Tech.*, 1344-1352 (Dec. 1974).

3 Ehrlich, R., Wygal, R.J., "Interrelation of Crude Oil and Rock Properties with the Recovery of Oil by Caustic Waterflooding", paper *SPE 5830*, presented at the Society of Petroleum Engineers of AIME Symposium on Improved Oil Recovery, Tulsa, Oklahoma (March 22-24, 1976).

4 Jennings, Jarley, Y., Jr., "A Study of Caustic Solution-Crude Oil Interfacial Tensions", *Soc. Pet. Eng. J.*, 15, No. 3 197-202 (1975).

5 Novosad, Z. *et al.*, « Comparison of Oil Recovery Potential of Sodium Orthosilicates and Sodium Hydroxide for the Wainright Reservoir, Alberta", *Petroleum Recovery Inst., Report* No. 81-10, Alta, Canada (July 1981).

6 Burk, J.H., "Comparison of Sodium Carbonate, Sodium Hydroxide, and Sodium Orthosilicate for EOR", *SPE Reservoir Engineering*, 9-16 (Feb. 1987).

7 Abdel-Waly, A.A., "Improving the Recovery of Some Egyptian Petroleum Crudes by the Adjustment of Injection Water Salinity", *Ph. D. Thesis*, Cairo University (1965).

8 Cooke, C.E., Williams, E.R., Kolodize, P.A., "Oil Recovery by Alkaline Waterflooding", *J. Pet. Tech.*, 1365-1374 (Dec. 1974).

9 Dokla, M.E., Sayyouh, M.H., Totonji, A., "Application of Caustic Waterflooding to Saudi Reservoirs", *Proceedings, AmSE 8th Annual Conference*, Lafayette (Sept. 1982).

10 Sayyouh, M.H., *Improved Oil Recovery Methods*, Energy Research Centre (ERC), Cairo University, (March 1986).

11 Mayer, E.H., Berge, R.L., Carmichael, J.D., Weinbrandt, R.M., "Alkaline Injection for EOR. A Status Report", *J. Pet. Tech.*, (Jan. 1983).

12 Raimondi, P.R., Gallagher, B.J., Ehrlich, R., Messner, J.H., Bennet, G.S., "Alkaline Waterflooding: Design and Implementation of a Field Pilot", *J. Pet. Tech.* (Oct. 1977).

13 Institute of Petroleum "Standard Methods for Testing Petroleum and Its Products", (1948).

Definitive manuscript received in November 1988