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PETROLEUM ENGINEERING

New Results on the Application of Alkaline Waterflooding to High Acidity Crude oil

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Abstract. 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, alkali type, temperature and 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 this crude oil and formation water decreases with increasing alkaline concentration until it reaches a minimum, after which it increases again with 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 which increase by the addition of alkaline solutions. Displacement floods in a 5-spot quadrant 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 the 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 yet been reported in the literature). Sodium hydroxide slugs produce more oil recovery than sodium carbonate slugs. Oil recovery increases with increasing temperature and decreasing oil viscosity.

Introduction

Displacement of oil by alkaline solutions in an important process [1-12]. Four different mechanisms have already been proposed to exaplin the displacement process of oil by alkaline solutions. In all these mechanisms, reaction between the alkaline solution and certain 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 areal sweep efficiency. In all cases, the interfacial tension is lowered by the emulsification process, and under certain conditions, the rock wettability may be altered either from oil-wet to water-wet or the reverse [8,9]. This wettability change results in an increase in oil recovery regardless of the direction of wettability reversal.

The South Geisum field is an off-shore field located at the southern end of the Gulf of Suez adjacent to the Red Sea, off-shore Egypt. The South Geisum oil accumulation in the South Geisum area in the southern portion of the lease is in Cretaceous and Nubia sandstone and fractured granite basement and occurs at an average depth of about 5000 feet subsea. The Nubia sandstone and fractured granite basement directly underlie the Cretaceous sandstone. The reservoirs are characterized by a relatively high dip angle towards the south, and by heavy faulting.

South Geisum crude oil is highly acidic, dark black, viscous, thick, and sticky with gravities in the range of 17-24° API. The average oil viscosity is about 21 cp under reservoir temperature of 60°C. The salinity of formation water is about 200,000 ppm.

Since the main significant characteristic of the crude oil of South Geisum field is its high acidity (4.38 mg KOH/g), this may make Geisum oil field a good candidate for successful enhanced recovery by alkaline waterflooding. Therefore, this investigation was devoted to studying the displacement of this crude by alkaline waterflooding and to investigate 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.

Experimental Work

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 crude oil viscositys at laboratory temperature was 138 cp.

A Genco du Nouy tensiometer was used to determine the interfacial tension between oil and water and between oil and alakaline solution. The instrument is equipped with a temperature control system in which water of constant temperature is circulated through a glass cup jacket. Interfacial tensions between South Geisum crude oil and both brine and alkaline water were measured at temperatures of 25° and 55°C. The very low values of interfacial tension could not be obtained by the Genco du Nouy tensiometer.

The contact angles that the oil droplet makes with a quartz plate in the presence of brine and alkaline solutions were measured at different temperatures of 25° and 55°C. The oil droplet was placed in contact with the downward surface of a quartz plate immersed in formation water or alkaline solution in a glass container. The oil droplet was photographed at periodic time intervals (1 hr.) 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 hrs while at 55°C this time was less than 6 hrs. By using a slide projector, the dimensions of the drop were measured, and the contact angle (θ) was calculated from the following formula:

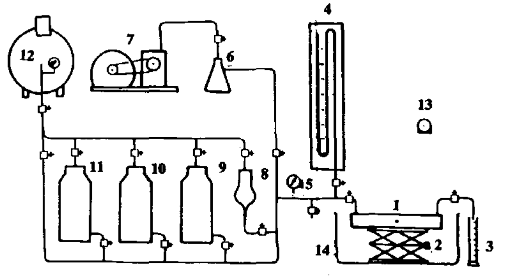
$$\tan(\theta/2) = D/2H$$

where H and D are dimensions of the oil droplet. Contact angles from 0 to 90 are water-wet, and from 90-180, oil-wet.

Displacement Experiments

The apparatus used in the displacement experiments is represented schematically in Fig. 1. The model used was a quadrant of a five-spot model made from prespex which allows 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 diagnoal. 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.

The model was packed homogeneously with a Maadi sand mixture. This sand pack had a permeability of about 5.2 darcies. The sand was washed by tap water, then by a dilute HC1 solution and again by distilled water. The experimental system was then completely evacuated from air 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



1. **Quadrant of five spot model**
2. **Movable horizontal platform**
3. **Graduated cyclinder**
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. **Stop watch**
14. **Water bath, heater and adjustable thermostat**

Fig. 1. Schematic diagram of the displacement apparatus

the sand packs was in the range of 0.34. Absolute permeability was obtained by circulating formation water at a given pressure drop across the sand pack. The following equation for a two dimensional sand pack was used to calculate absolute permeability:

$$Q = [\,3.54\,Kh\,(P_i - P_o)\,]/\{\,[\,\ln(d/r_w) - 0.619\,]\,\mu\}$$

where:

Q	=	flow rate, cc/sec
K	=	absolute permeability, darcy
h	=	thickness of the column, ft
P_i	=	pressure at the inlet, psi
P_o	=	pressure at the outlet, psi
μ	=	viscosity, cp
d	=	distance between injector and producer, cm
r_w	=	radius of the production well, cm

The model was then saturated with oil by the continuous injection of oil until the water cut in the effluent was less than 1%. At this point, the initial saturation conditions of the reservoir were assumed to occur. An alkaline slug was then injected into the sand pack, followed by approximate four pore volumes of displacement of seawater. The produced liquids were collected continuously and the amount of oil and water in the sample were determined and recorded with time. The water/oil relative permeability ratio versus terminal water saturation is shown in Fig. 2. Table 1 is a summary of the displacement floods.

In this work, the displacement of South Geisum crude oil by alkaline solutions of different concentrations under the same conditions of porosity and permeability was carried out. No measurements of the effects of alkali-rock reactions on porosity and permeability were made in this study.

All chemical solutions were freshly prepared just before using them to avoid any effect of air exposure or precipitation. All displacement data were the saverage of at least two runs of good reproducibility.

Results and Discussion

Effect of Alkaline (NaOH) Concentration on Oil Recovery

Fig. 3 shows the cumulative oil recovery and oil cut in the produced samples versus pore volumes of water injected using 15% pore volume (PV) slug size of different NaOH concentration 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.

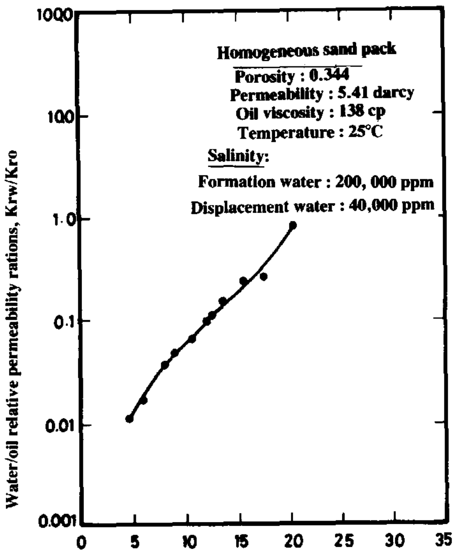


Fig. 2. Water/oil relative permeability ratio versus terminal water saturation.

It is seen from these experiments that alkaline waterfloods recover more oil than do conventional waterfloods. This increase in ultimate oil recovery is evidenced by production of a large oil-water bank or by delayed oil production. Since the 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 between alkali and organic acids occurring in the crude oil. These reactions result in the formation of surface active materials (soaps) whose absorption on the oil-water interfaces decreases the interfacial tension between oil and water, thus yielding an oil-water emulsion. This formed emulsion can be entrained into the alkaline flow to be produced, or entrapped again, resulting in better sweep efficiency. The entrainment or entrapment and the pore size distribution of the formed emulsions depends on the interfacial tension and on the applied pressure gradient 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. Fig. 5 illus-

Table 1. Summary of displacement floods

Run	Porosity (%)	Absolute permeability (darcy)	Initial oil saturation (% PV)	Alkali type	Alkaline concentration (wt %)	Recovery at 1.5 PV (% OIP)	Tempe-rature (°C)	Slug size (% PV)
1	34.4	5.406	83.9	–	–	25.4	25	0
2	33.3	5.381	85.3	NaOH	1	28.6	25	15
3	34.2	5.350	84.4	NaOH	2	30.5	25	15
4	33.3	5.432	85.3	NaOH	3	33.4	25	15
5	35.1	5.426	85.9	NaOH	4	34.0	25	15
6	33.8	5.392	92.1	NaOH	5	29.6	25	15
7	33.8	5.426	88.2	NaOH	6	28.1	25	15
8	32.7	5.426	89.8	NaOH	7	26.2	25	15
9	34.2	5.415	87.0	NaOH	4	20.0	25	25
10	34.4	5.410	86.5	NaOH	4	17.0	25	30
11	33.3	5.426	90.0	Na_2Co_3	4	14.2	25	15
12	32.4	5.324	87.7	NaOH	4	45.5	55	15
13*	35.1	5.420	84.8	NaOH	–	55.6	25	0
14*	34.0	5.390	85.4	NaOH	0.5	57.5	25	15
15*	34.4	5.417	83.2	NaOH	1	62.0	25	15

* 50% crude oil + 50% kerosine.

trates the interfacial tension between South Geisum crude oil and NaOH solutions of 200,000 ppm NaC1 salinity versus NaOH concentration at a temperature of 25°C. It can be seen that increasing the NaOH concentration decreases the interfacial tension until a region of least interfacial tension is reached at 3 to 4 weight % of NaOH concentration. Further increases in NaOH concentration above this level results again in the increase of the interfacial tension.

Results of contact angle measurements are shown in Fig. 6 using different NaOH solution concentrations in 200,000 and 40,000 ppm NaC1 brine at a temperature of 25°C. Fig. 6 shows that the contact angle is affected by the alkaline concentration in such a manner that the presence of 0.5% by weight NaOH resulted in an abrupt increase in the contact angle. For the 200,000 ppm NaC1 brine the contact angle increased from 127°C to 172°C at 0.5% NaOh concentration. Increasing NaOH concentration kept the contact angle at the same high values range (above 170°C) until the concentration reached 3% NaOH, after which, further increases in NaOH concentration resulted in a decrease in the contact angle to 160°C at 4% NaOH and to 145°C at 10% NaOH concentration.

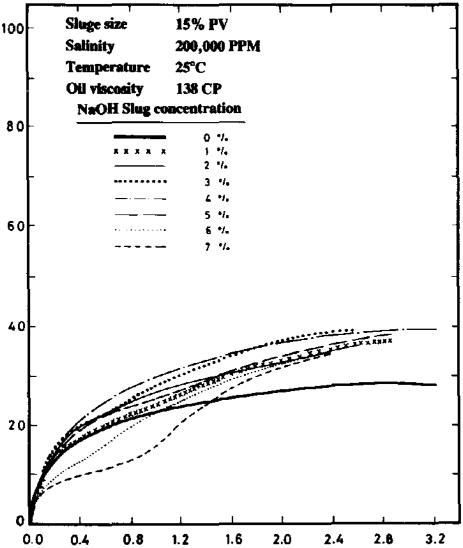


Fig. 3. Effect of NaOH slug concentration on oil recovery by alkaline waterflood.

Adhesion tension (σ_{wo} cosθ) at different NaOH concentrations was calculated by using both interfacial tension and contact angle. Fig. 7 shows the adhesion tension versus NaOH concentrations. Based on Fig. 7, it can be said that the best displacement conditions are in the region of about 3% NaOH concentration. Although, this region is characterized by higher contact angle values than the surrounding regions, the excessive decrease of the interfacial tension compensates for the contact angle increase, leading to better displacement conditions. On the contrary, at higher concentrations, contact angle decreases and the interfacial tension increases but by a larger factor yielding poorer displacement conditions. This result supports the conclusion that interfacial tension lowering and temperature are important mechanisms for improving displacement efficiency.

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

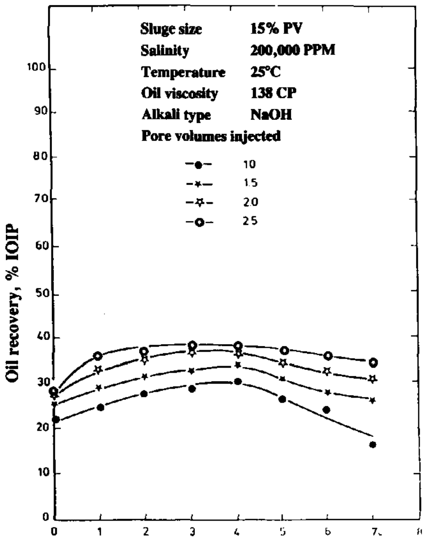


Fig. 4. Effect of slug concentration on oil recovery at different pore volumes of injected displacement water.

waterflooding (mobility ratio at average water saturation and viscosity ratio of 92 is equal to 9.2). On the other hand, although oil recovery during early times for higher NaOH concentrations is slow, 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 yields a comparable ultimate oil recovery at high and low alkaline slug concentrations. This leads to the conclusion that, at a large number of pore volumes of water injected, less ultimate oil recovery is obtained as a result of increasing alkaline slug concentrations greater than 6. 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% by 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, as shown in Fig. 4.

This result does not correlate directly to the interfacial tension measurements and hence to the adhesion tension results (the best region for the displacement pro-

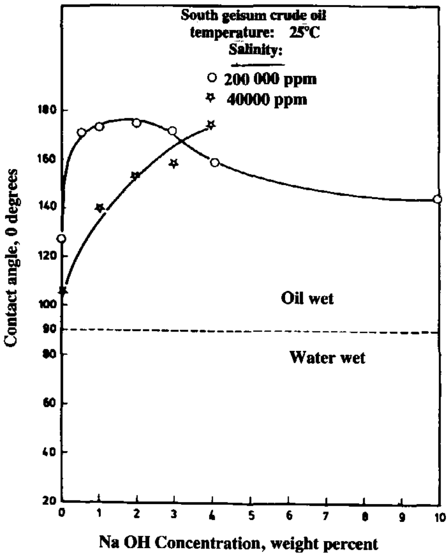


Fig. 5. Interfacial tension between South Geisum crude oil and NaOH solution as function of NaOH concentration, temperature and alkaline type.

cess is at 3% NaOH concentration, 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 absorption of alkali on the grain surfaces. This reduction of concentration causes a little shift in the adhesion tension results as compared to displacement results. This shift is dependent on the initial alkaline concentration and on the time of contact with the porous medium. NaOH slugs of concentrations equal to or lower than 4% are expected to lose some of their effective concentration due to absorption and mixing with connate and displacement water. These concentrations will still be within the range of the adhesion tension values close to zero and this gives favorable oil displacement. This situation is not quite the same in case of higher NaOH concentration slugs which also lose some of their concentration with time but in the direction of the region of better displacement of the adhesion tension close to zero. As shown in Fig. 3, at the early stages of injection higher concentration displacement floods are characterized by lower oil production than that of a conventional waterflood. After these early injection stages delayed oil-water banks are produced. This early lower production can be

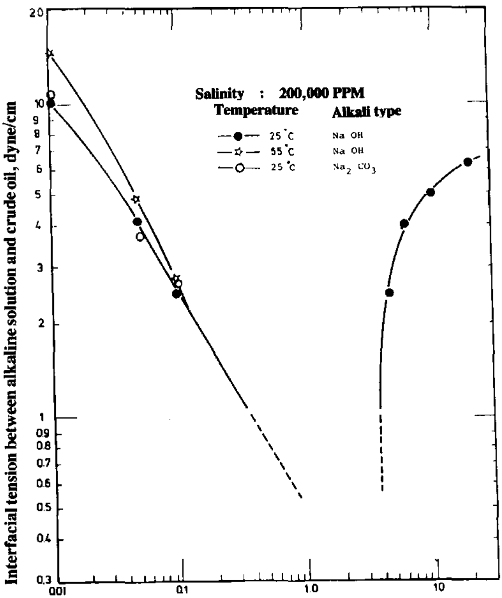


Fig. 6. Contact angle as function of alkaline concentration and salinity

attributed to the unfavourable 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 displacement water in the rear of the bank and to absorption 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 favourable NaOH concentration. This favourable slug concentration gives the least interfacial tension between oil and alkaline solution and contributes to the formation and entrainment of oil-water emulsions in the alkaline flow resulting the production of this emulsion oil. 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.

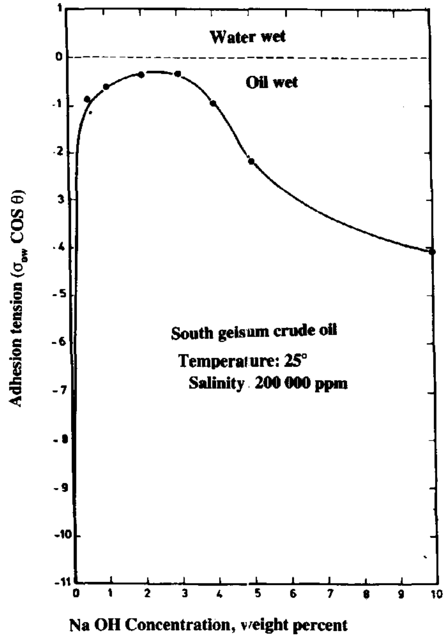


Fig. 7. Adhesion tension (σ_{wo} cosθ) versus NaOH concentration

Effect of Slug Size

Fig. 8 shows the production histories for the 0, 15, 25 and 30% pore volumes alkaline slug size displacement at a temperature of 25°C. Cumulative oil recovery is expressed as a percentage of the initial oil in place. This figures shows the behavior of the oil-water bank for varying alkaline slug sizes using a 4% by 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 from Figs. 8 and 9 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, the oil recovery was 25% of the initial oil inplace at 1.5 pore volumes injected, whereas for 30% PV slug size, the recovery was reduced to 16% for the same pore volumes injected. This effect was not reported in the literature.

The following discussion is an effect to systematically examine the effect of alkaline slug size on the mechanism of displacement of South Geisum crude oil by an 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. Production of both oil and water at a certain producing rate ratio starts at oil bank breakthrough. The observed fluctuations 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-water bank for a varying alkaline slug size with a concentration of 4% by weight of NaOH. The distinct feature in this figure is that the oil-water bank was larger when using a 15% PV slug size and hence a greater recovery was obtained. It is apparent from the production histories that a significantly wider bank exists with a 15% PV slug size as compared to that of either the 25 or 30% PV plug sizes.

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.* areal 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 still arising is a decrease of oil recovery with 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 injected slug concentration, 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. In using variable slug sizes, it is necessary to consider the effect of NaC1 concentration change on the displacement process.

Fig. 10 shows the interfacial tension between crude oil and water at two different salinity levels, namely 40,000 and 200,000 ppm NaC1 (displacement seawater and slug salinities, respectively). It is clear that the interfacial tension decreases with an increase in NaC1 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 salinity prevents these surface active materials from being dissolved in the water phase thus causing them to be adsorbed on either the mineral surface of the rock or the oil water interface. This in turn may either enhance the oil-wetting condition or decrease the oil-water interfacial tension. The prevention of the surface active materials from dissolution into water, also affects the type of the oil-water emulsion which can be

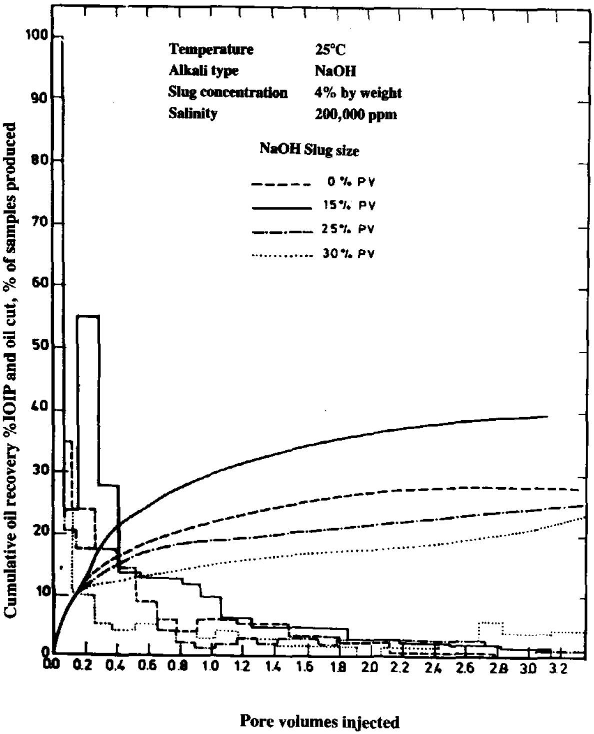


Fig. 8. Effect of alkaline slug size on oil recovery by alkaline waterflood

formed. At higher salinities, the type of emulsion could be a water-in-oil emulsion, which differs from an oil-in-water emulsion in that it needs a higher pressure gradient to mobilize it [7,12]. This mechanism can increase the oil recovery only if the interfacial tension is very low. A low interfacial tension results in a lowering of the capillary forces to a degree sufficient to be overcome by the pressure gradient. But, to have this minimum interfacial tension, caustic concentration must be at a favorable level which corresponds to 4% NaOH concentration at 15% PV. This caustic concentration can only be achieved in the porous medium, 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 with the alkaline concentration and the

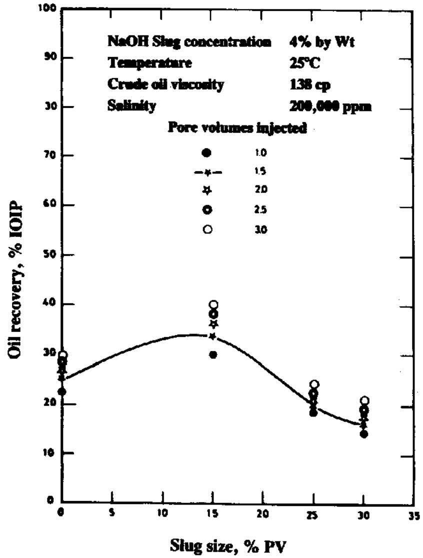


Fig. 9. Effect of alkaline slug size on oil recovery by alkaline waterflood at different pore volumes of injected displacement water.

salinity to provide the optimum conditions of 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 between the effect 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.

Fig. 11 shows the cumulative oil recovery and production histories of these alkaline waterfloods. It is seen from this figure that less oil recovery was obtained in the of Na_2CO_3. The Na_2CO_3 solution of 4% by weight concentration has a pH value of 9.77, while the pH value of NaOH solution of the same concentration and salinity is 11.35. This difference in pH value may explain the decrease of oil recovery in the case where Na_2CO_3 is used.

Fig. 5 shows the oil-water interfacial tension versus alkaline concentration. It is clear from this figure that interfacial tension decreases with low values of Na_2CO_3 concentration. A comparison between the inter-facial tension between a 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. 5), then solid-water interfacial tensions was altered by a change in the pH value of the alkaline solution. As a result of this variation, a different oil recovery was obtained in each.

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 afects, to a greater 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.

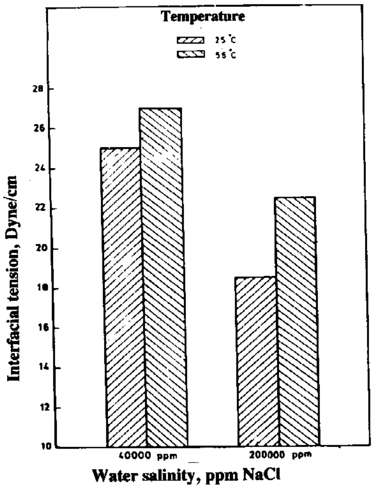


Fig. 10. Interfacial tension between South Geisum crude oil, and sea water and formation water.

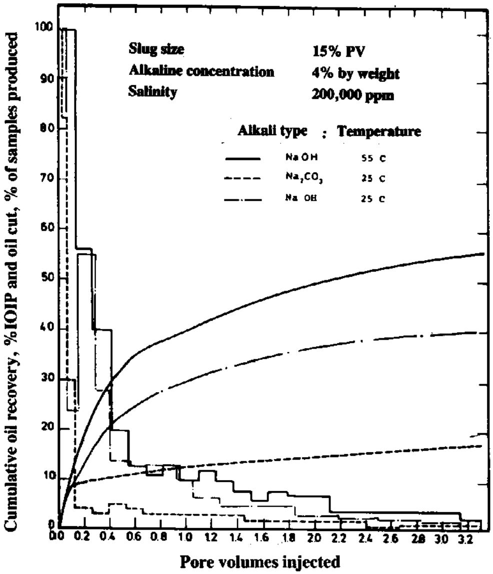


Fig.11. Effect of temperature and alkali type on oil recovery by alkaline waterflood

Fig. 11 also shows the production histories of two alkaline water floods under the same conditions of 4% by weight NaOH concentration and 15% PV slug size, but at two different the temperature levels of 25°C, and 55°C respectively. In order to cancel the effect of oil expansion on the recovery mechanism as a result of increasing temperature, the formation water saturation process as well as the oil saturation one were carried out at the same temperature. Also, the recovery calculations were based on the oil produced at the same temperature.

It is seen from Fig. 11 that a substantial increase in oil recovery was obtained when temperature increased from 25°C 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. 12 no significant change in the contact angle was observed as a result of increasing the temperature. From Fig. 5, which shows showing the interfacial tension between oil and alkaline solutions at both 25°C and 55°C, it can be seen

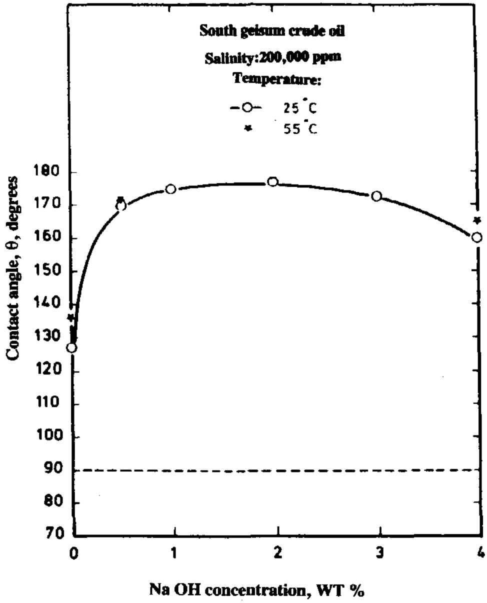


Fig. 12. Effect of temperature on contact angle

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 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.

Fig. 13 represents the production history for a conventional waterflood using a South Geisum crude oil (138 cp) and Geisum crude mixed with kerosene (5.5 cp) at the same temperature of 25°C. This figure shows that oil recovery increases with

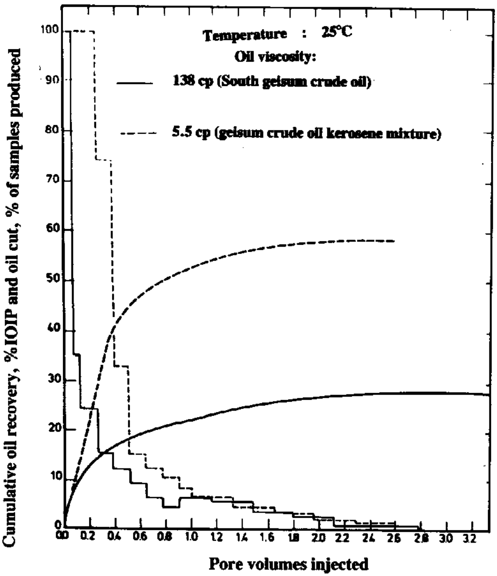


Fig. 13. Effect of oil viscosity on oil recovery by conventional waterflood

decreasing crude viscosity (*i.e.* decreasing mobility ratio). For example, at 1.0 PV water injected, oil recovery at the high viscosity flood was 22% of the initial oil-in-place, while for the low viscosity flood the recovery was 65% of the initial oil-in-place. The water-oil relative permeability and mobility ratio is much higher when using a high viscosity crude oil and a hence lower displacement efficiency was obtained for this case.

Fig. 14 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-kerosene 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, water-oil ratio is higher in the case of using low viscosity crude than in the high viscosity flood. This can be attributed to the improvement in areal sweep efficiency in the case of using lower crude oil viscosity (*i.e.* lower mobility ratio).

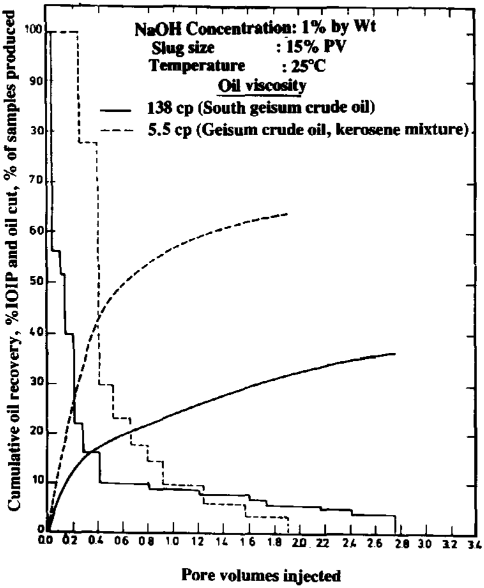


Fig. 14. Effect of oil viscosity on oil recovery by alkaline waterflood

Conclusions

The following conclusions were obtained from this work:

1) 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% by weight NaOH concentration after which it increases again with further increase in the alkali concentration.

2) Contact angle measurements under the conditions of formation water salinity and a temperature of 25°C indicated a preferentially oil-wet system.

3) Alkaline NaOH waterfloods recover more oil than does the conventional waterflood. This increase in ultimate oil recovery is evidenced by either production of a large oil-water bank or delayed oil production.

4) At early stages of displacement, oil recovery increases with increasing NaOH slug concentration until it reaches a maximum at 4% by 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.
5) At 4% by 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 further increase in slug size results in decreasing oil recovery.
6) At applied conditions of 15% PV slug size, 4% by weight slug concentration and 25°C temperature, sodium hydroxide slug produces more oil recovery than does sodium carbonate slug.
7) 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.*, Jan. (1976), 85-92.
[2] Jennings, H.Y.; Johnson, C.E. and McAuliffe, C.D. "A Caustic Water-flooding Process for Heavy Oils." *J. Pet. Tech.*, December (1974), 1344-1352.
[3] Ehrlich, R. and 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 Tension." *Soc. Pet. Eng. J.* 15, No. 3 (1975), 197-202.
[5] Novosad, Z. *et al.* "Comparison of Oil Recovery Potential of Sodium Ortho Orthosilicates and Sodium Hydroxide for the Wainright Reservoir, Alberta." *Petroleum Recovery Inst. Report*, No. 81-10 Alta; Canada (1981).
[6] Burk, J.H. "Comparison of Sodium Carbonate, Sodium Hydroxide and Sodium Orthosilicate for EOR." *SPE Reservoir Engineering*, Feb. (1987), 9-16.
[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. and Kolodize, P.A. "Oil Recovery by Alkaline Waterflooding." *J. Pet. Tech.*, Dec. (1974), 1365-1374.
[9] Dokla, M.E.; Sayyouh, M.H. and 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*. Cairo University: Energy Research Centre (ERC), 1986.
[11] Mayer, E.H.; Berge, R.L.; Carmichael, J.D. and Weinbrandt, R.M. "Alkaline Injection for EOR - A Status Report." *J. Pet. Tech.*, Jan. (1983), 209-221.
[12] Raimondi, P.R.; Gallagher, B.J.; Ehrlich, R.; Messner, J.H. and Bennet, G.S. "Alkaline Waterflooding: Design and Implementation of a Field Pilot." *J. pet. Tech.*, (1977), 1359-1368.
[13] Institute of Petroleum. *Standard methods for Testing Petroleum and Its Products*. Cairo: Institute of Petroleum, 1948.

نتائج جديدة على تطبيق الغمر بالمياه القلوية لاستخلاص خام الزيت المرتفع الحموضة

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ملخص البحث. إن الهدف الرئيس من هذا البحث هو دراسة الاستخلاص المُحسَّن للخام المرتفع الحموضة (خام جنوب جيسوم) بواسطة المحاليل القلوية. ولقد تم دراسة الخواص المختلفة لخام جنوب جيسوم وأهمها درجة الحموضة والشد البينسطحي وزاوية الالتصاق. وأجريت تجارب الإزاحة لدراسة تأثير درجة تركيز القلوي ونوعه ودرجة الحرارة واللزوجة على العائد النفطي.

ولقد وجد أن حموضة خام جنوب جيسوم حوالي ٤,٣٨ مجم هيدروكسيد البوتاسيوم لكل جم من الخام. ووجد أن الشد البينسطحي بين الزيت الخام والمياه المصاحبة تقل بزيادة درجة التركيز القلوي حتى تصل إلى أقل ما يمكن وبعدها تزداد مرة أخرى بزيادة التركيز القلوي. وكذلك فإن الشد البينسطحي بين الزيت الخام والماء المزاح يقل بزيادة تركيز القلوي. ودلت قياسات زاوية الالتصاق وجود ظروف التبلل بالزيت وتزداد بإضافة المحاليل القلوية.

ولقد أظهرت تجارب الإزاحة في المراحل الأولى من إزاحة الزيت أن العائد النفطي يزداد بزيادة درجة التركيز القلوي حتى يصل إلى أعلى ما يمكن عند ٤٪ بالوزن هيدروكسيد الصوديوم. ومن الناحية الأخرى بعد المراحل الأولى من الإزاحة وبعد حقن عدة أحجام من الحجم الفراغي فإن العائد النفطي تقريبا متساوٍ ولا يعتمد على درجة التركيز. ووجد أيضا أن العائد النفطي يزداد بزيادة الكتلة القلوية المحقونة حتى تصل إلى أقصى حد لها ١٥٪ وبعدها يقل العائد بزيادة الكتلة وهذه نتيجة جديدة حتى الآن. ووجد أن حقن كتل هيدروكسيد الصوديوم تعطي عائد نفطي أكبر من حقن كتل كربونات الصوديوم. وكذلك وجد أن العائد النفطي يزداد بزيادة درجة الحرارة ولزوجة الخام.