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Effects of Stimulating Indigenous Bacteria in Oil Reservoirs on Relative Permeability Curves

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Abstract

Laboratory studies show the existence of some strains of bacteria in field crude oils and formation waters. This work is concerned with studying the effect of indigenous bacterial activities on the relative permeability of samples from Egyptian fields. Such study is an original contribution to the knowledge of microbial enhanced oil recovery.

Phase volume studies were carried out using two types of crude oils having different spores forming bacteria. The relative permeability experiments were conducted in sandstone cores. Some available nutrient solutions being used in the field tests were also used.

Based on the phase volume measurements, it was found that the indigenous microbial growth was better after two days incubation time with 1% molasses concentration as a nutrient. Residual oil saturation was found to decrease with stimulating the indigenous bacteria in the crude oils by using 1% molasses concentration. Presence of 1% molasses concentration increases the relative permeability to oil. It was found also that crude oil A, which contains *Clostridium sp.* and *Bacillus sp.*, gave better relative permeability curve behavior than that of crude oil B, which contains *Bacillus sp.* only. Salinity increase decreases the relative permeability to oil. In the presence or absence of molasses, no clear trend of absolute permeability on oil-water relative permeability curves was observed.

The results obtained are discussed and analyzed in terms of the system phase variation, interfacial forces, wettability characteristics, hydrogen ion concentrations, viscosity effects, and mechanical and mineralogical analysis of the cores.

Introduction

The earliest realization that certain microbes might be useful for enhancement of petroleum recovery was made in 1926, when Beckman[1] proposed that certain bacterial metabolites would assist in the release and transport of oil in the geological structure. Subsequent laboratory and field studies[2-6] have shown that microorganisms can produce effective products similar to those described for chemical and miscible EOR processes. These products can assist in the release of oil from the capillary pores and can improve the sweep and displacement efficiencies so that: (1) the microbial production of gases can improve the flow characteristics, (2) the microbial production of solvents can reduce the interfacial tension, (3) the microbial production of organic acids can result in the dissolution of carbonates in source rock and increase the rock permeability, (4) The microbial production of polymers can increase the viscosity of the water in the waterfloods and/or plug the high-permeability zones of the reservoir rock and thus divert the reservoir fluids to previously unswept areas of the reservoir, (5) and the microbial production of surface active compounds (surfactants) can reduce oil-water interfacial tension and cause emulsification, and can alter the wettability of the reservoir rock. Also, the microbial growth on rock pore surfaces can plug the high-permeability zones. Another important discovery is the ability of certain bacteria to eliminate paraffin deposition around the producing wells. During the last ten years, several studies on the microbial characteristics and metabolic activity of bacteria for improve oil recovery in the middle east area have been carried out.[7-13] Based on these studies, MEOR should be able to recover up to 30 % of the residual oil under reservoir conditions.

Relative permeability data are very important for petroleum reservoir engineering studies and projects.[14] These data are used in almost all the engineering calculations that involved the movement of several fluids together in the reservoir. The data are used in making engineering estimates of productivity, injectivity, residual hydrocarbon saturation, irreducible water saturation, and ultimate recovery from reservoir for evaluation and planning of production operation, and also can be used to diagnose formation damage expected under various operational conditions. Also, the curve of the relative permeability can be used as a tool in the evaluation of any enhanced oil recovery method as it reflects any change in the wettability and in the capillary number. Due to the importance of relative Permeability data, it is necessary to know that " is the relative permeability affected by the growth of bacteria in porous media? " In this study, an attempt has been made to answer this question.

The main objective of this study is to investigate the effect of indigenous bacteria activity on the relative permeability curves. The parameters investigated are molasses concentration, crude oil type, formation water salinity, and absolute permeability.

Experimental Work

The experimental work was performed to achieve the objective of this research. Therefore, at the start of the work, the effect of nutrient type and concentration, and the effect of incubation time on stimulating the indigenous bacteria were studied through measuring the changes of the aqueous phase volume. The phase volume studies were carried out using two types of crude oil having different spores forming bacteria (Crude Oil A and Crude Oil B) and three types of nutrient (molasses, dextrose and sucrose). Then, twelve unsteady state relative permeability tests were conducted using four sandstone core samples, in order to study the effect of molasses concentration, crude oil type, salinity, and absolute permeability on this measurments. The conditions of these tests are summarized in Table 1. Additional information about the effects of nutrition conditions on the bacterial growth was obtained through measuring the interfacial tension between crude oils and the nutrient solutions, the hydrogen ions concentration (pH) of the aqueous phases, and the viscosity of the nutrient solutions. Also, mechanical and mineralogical analysis of the core samples was carried out.

A "Core-Lab" displacement type water-oil relative permeability apparatus is used to perform water-oil relative permeability tests. This apparatus was designed to permit the simultaneous measurement of volumes and rates of flow of water and oil produced from a sample subjected to an external water drive under a constant pressure differential. The accumulative volumes of produced water and oil are collected in the receiving tubes. The resultant data, together with time and differential flooding pressure measurements, are used to calculate relative permeability relationships using Welge's and Johnson's method.[15,16]

Reproducibility of Relative Permeability Data. Two tests, Test 1 and Test 2, were performed in the same conditions to test the reproducibility of data. Fig. 1 illustrates that the relative permeability curves of these testes are identical. The identity of the curves means good reproducibility of data.

Results and Discussion

Role of Microorganisms on the Solution Phase Behavior. Fig. 2 shows the effect of the concentrations of the three nutrient types (molasses, dextrose and sucrose) on the ratio of the aqueous phase volume to the total liquid (aqueous phase + Crude Oil A) volume using 4% NaCl at 40°C after two days incubation time. This figure illustrates that 1% molasses solution produced the lowest (best) aqueous phase volume. This behavior may be attributed to the fact that molasses is a rich nutrient medium for bacterial growth. This may increases biomass generation that increases bacterial production of acidic and surface active metabolic solutions.[17] Fig. 3 is plot of the ratio of the aqueous phase volume to the total liquid (aqueous phase + Crude Oil A) volume after three different incubation time (two, four and six days) versus the molasses concentrations using 4% NaCl at 40°C. As shown in this figure, the aqueous phase volume increased with time. This behavior may be related to the death of bacteria. The death of the bacteria may be attributed to many reasons such as starvation environment due to exhaustion of nutrients and changing environmental properties as a result of the metabolic products of bacteria with time.[18] Also, this figure indicates that the best volume change (i.e., minimum aqueous phase volume) can be obtained with 1% molasses after two days incubation time. It should be noted that the above-mentioned results were also obtained when using the same nutrient solutions with Crude Oil B as shown in Fig. 4 and Fig. 5.

Effect of Molasses Concentration on Relative Permeability Data. Fig. 6 and Fig. 7 show the effect of molasses concentration on water-oil relative permeability of Sample 1 and Sample 2, respectively, using Crude Oil A with 4%NaCl formation water salinity after two days incubation time at 40°C. While, Fig.8 shows the same effect on water-oil relative permeability curve of Sample 1 using Crude Oil B under the same conditions. The results of the above-mentioned figures are summarized in Table 2.

Generally, it can be observed from Figs. 6, 7 and 8 that the presence of 1% molasses concentration as a nutrient with Crude Oil A or B has led to an increase in the relative permeability to oil and a decrease in the relative permeability to water. Also, it can be seen some shift in the crossover point of the oil-water relative permeability curve. This shift may be indicative of a change in the rock wettability towards more water wettability. Moreover, residual oil saturation was found to decrease with stimulating the indigenous bacteria in the crude oils by using 1% molasses concentration as a nutrient. The decrease in the residual oil saturation led to increase in the recovery in the range of 5.2-7.0 %.

To analyze the results of the relative permeability curves, the IFT measurements between the crude oils and media containing microbial metabolites, the viscosity measurements of the nutrient solutions, and the pH measurements of the aqueous phases were carried out. The results of these measurements are presented in Table 3.

It is clear from the IFT measurements that the IFT was reduced when using Crude Oil A/brine system containing 1% molasses at 0.0 hrs, and when using Crude Oil A/medium containing microbial metabolites after 48 hrs. incubation time. The same results were obtained when using Crude Oil B as indicated in Table 3. The reduction in the IFT is attributed to two main reasons. The first one is the presence of molasses which gives solutions have low free energy.[19] The second reason is that the bacterial growth and the production of surface active compounds such as surfactants and acids. The reduction of the IFT is thought to be the main reason for (1) the decrease in the residual oil saturation and thus the increase in the oil recovery, (2) the increase in the oil relative permeability and (3) the shift in crossover point of the oil/water relative permeability curve towards more water wettability. Many investigators[20-22] have been studied the effect of IFT on the relative permeability. They reported results consistent with the above-mentioned results.

The presence of 1% molasses concentration as a nutrient with both Crude Oils A and B increases the value of the viscosity of the aqueous phase during the microbial action on the crude oil as shown in Table 3. The increase in the viscosity of the aqueous phase is related to bacterial growth and production of some polymers. The production of these polymers may be the main reason for reducing the relative permeability to water as shown in Figs. 6, 7 and 8. This may be attributed to the high resistance to flow, which is resulted due to flow of bio-polymers through the porous media; and is also a result of the retention which occurs by polymer adsorption on the surface of the sand particles and by mechanical retention of polymer molecules.[23]

It is noticeable also from the pH measurements that after two days incubation time, the value of the pH of the aqueous phase with both Crude Oils A and B decreases in the presence of 1% molasses concentration. The lowering of the pH is a result of microbial growth. Microbial growth can cause the lowering of the pH either from respiratory metabolism or from production of acids. The previous studies by Premuzic and Lin[24] showed that lactic and carboxylic acids were present in the aqueous phase as microbial metabolites. It should be noted that the production of acid reduces the IFT between crude oil and aqueous phase as surfactant. Therefore, acids cause the same effect of surfactant.

Effect of Crude Oil Type on Relative Permeability Curves. Fig. 9 represents the effect of crude oil type on water-oil relative permeability curve of Sample 1 using 1% molasses concentration as a nutrient and 4%NaCl formation water salinity after two days incubation time at 40°C.

It can be noticed from Fig. 9 that, in the presence of 1% molasses concentration as a nutrient, the oil relative permeability curve that obtained when using Crude Oil A is higher than that obtained when using Crude Oil B. As the water saturation below 62.0 %, the water relative permeability curve that obtained when using 1% molasses concentration with Crude Oil A is lower than that obtained when using 1% molasses concentration with Crude Oil B. It is also seen from Fig. 9 and Table 2 that the shift in the crossover point of the oil–water relative permeability curve that obtained when 1% molasses was used with Crude Oil A is larger towards more water wettability than that obtained when 1% molasses concentration was used with Crude Oil B. Also, a large reduction in the residual oil saturation and consequently larger increase in the oil recovery were obtained when using Crude Oil A.

The above results can be better interpreted by using the IFT, viscosity, and pH measurement results which presented in Table 3. It should be noted that, after two days incubation time, large reduction in the IFT values between Crude Oil A and the nutrient solution and in the pH values of the nutrient solution were obtained compared to those with Crude Oil B. Also, Crude Oil A results in increase in the viscosity values of the nutrient solution compared to those with Crude Oil B. All of the results have led to conclude that using 1% molasses concentration as a nutrient with Crude Oil A gives better behavior compared to that with Crude Oil B. This may be due to the different bacterial content as well as properties and composition of the two crude oils used.[17,25] Crude Oil A contains *Clostridium sp.* and *Bacillus sp.*, while Crude Oil B contains *Bacillus sp.* only. Growth of these bacteria can create metabolic products such as acids, boisurfactant and boipolymers with different amount.

Effect of Formation Water Salinity on Relative Permeability Data. Fig. 10 shows the effect of formation water salinity on water-oil relative permeability curve of Sample 2 using Crude Oil A with 1% molasses concentration after two days incubation time at 40°C. The results of this figure are summarized in Table 4.

The results presented in Fig. 10 show a marked trend in the change in both the oil and the water relative permeability curves as the formation water salinity changed from 4% NaCl to 15% NaCl and from 15% NaCl to 20% NaCl. It will be noted that at a given saturation the relative permeability to oil decreases and the relative permeability to water increases as the formation water salinity increases. Fig. 10 and Table 4 illustrate that the reduction in the formation water salinity shifts the crossover point of the oil-water relative permeability curve towards more water wettability. Also, it is seen from the same figure and table that the salinity increase increases the residual oil saturation and consequently decreases the oil recovery.

According to the above results, salt concentration around 4% NaCl are expected to have better relative permeability curve behavior. It is believe that this is due to the effect of salt concentration on nutrient solutions properties during the microbial action on crude oil. As shown in Table 5, higher salt concentration gave (1) lower reduction in the IFT values between crude oil and nutrient solution, (2) lower reduction in the pH of the nutrient solution and (3) lower increase in the viscosity of the aqueous phase.

The changes in the solutions properties are attributed to the reduction in the bacterial growth as the salinity increases. So that, increasing NaCl concentration of the surrounding increases the osmotic pressure difference between the surrounding and the cytoplasm within the cell, which can result in dehydration of the cell. This may lead to plasmolyze the cells, which may reduce the bacterial activity followed by growth inhibition or death of the cell.[26] These events have led to decreases the amount of microbial products. Also, it should be noted that, relative solubilities of the surfactants in the oil and water can be varied significantly by changing the salinity of the aqueous phase. At low salt concentrations, most of the surfactant staying in the aqueous phase, while at high salt concentration, the surfactant preferentially dissolves into the oil phase. At optimal concentration, however, the surfactant concentration is the same in both oil and water which produces the lowest IFT.[27]

Effect of Absolute Permeability on Relative Permeability Curves. Figs. 11 and 12 represent the relative permeability curves of four samples of different absolute permeability (266 md, 872 md, 666 md, and 1550 md) using 0.0% and 1.0% molasses concentration, respectively, with Crude Oil A and 4% NaCl formation water salinity. As shown in each figure individually, in the presence or in the absence of molasses, there is no clear trend of absolute permeability on oil-water relative permeability curves. This result is consistent with that experimentally obtained by Morgan and Gordon.[28] They conducted tests for four sandstone samples from a reservoir rock with permeabilities ranging from 109 to 273 md. No clear effect of permeability on oil-water relative permeability curves was observed.

The obtained results may be attributed to change in the rock properties that control pore geometry. Therefore, mechanical and mineralogical analysis of the four cores was carried out to investigate the distribution of the grain size and to determine the amount and type of clay and non-clay minerals. The results[29] of this analysis showed that the samples have Uni-model grain size with the peak at 0.112 mm. However, the qualitative analysis of the samples showed that the mineral composition is mainly constituted of quartz. There are some other non-clay minerals in very small percentage such as feldspars, pyrite, dolomite, and calcium oxide. The X- ray diffraction of Sample 4 showed that the sample has no clay minerals. However, the X- ray diffraction of Sample 1,2, and 3 showed that the only clay mineral present in these samples is kaolinite. The relative quantity of clays in the samples is as follows:

1. The percentage of kaolinite mineral in the Sample 2 is four-times the quantity in the Sample 1.
2. The percentage of kaolinite mineral in the Sample 3 is double the quantity in the Sample 1.

From the above results, the small change of the clay percentage in the cores with the variation in the sorting or in the cementation is thought to be the main reason that has led us to say that " There is not constant true relation or correlation between the absolute permeability alone and the relative permeability; moreover, the rock properties that control the pore geometry must be take into consideration."

Conclusions

Based on the experimental conditions used in this work, the following conclusions can be obtained:

1. For both types of crude oil and using 4% NaCl at 40°C, 1% molasses concentration as a nutrient was the optimum concentration at which the indigenous microorganisms have given a minimum aqueous phase volume than those obtained at other tested molasses, dextrose and sucrose concentrations.
2. For the tested incubation times, the results showed that the indigenous microbial growth was better after two days incubation time.
3. Presence of 1% molasses concentration as a nutrient with Crude Oil A or B has led to an increase in the relative permeability to oil, a decrease in the relative permeability to water, some shift in the crossover point of the oil-water relative permeability curve towards more water wettability, and a decrease in residual oil saturation that led to an increase in the oil recovery.
4. With stimulating the indigenous bacteria in the crude oils by using 1% molasses concentration as a nutrient, it was found that a decrease in the IFT values between crude oils and nutrient solutions, an increase in the viscosity values of the aqueous phases, and a decrease in the pH of the nutrient solutions.
5. Crude Oil A, which contains *Clostridium sp.* and *Bacillus sp.*, gave more better relative permeability curve behavior than that of Crude Oil B, which contains *Bacillus sp.* only.
6. During the microbial action on the crude oils, large reduction in the IFT values between Crude Oil A and the nutrient solution and in the pH values of the nutrient solution were obtained compared to those with Crude Oil B. Also, Crude Oil A results in large increase in the viscosity values of the nutrient solution compared to those with Crude Oil B.
7. Salinity decrease increases the relative permeability to oil, decreases the relative permeability to water, and shifts the crossover point of the oil-water relative permeability curve towards more water wettability. Also, the salinity decrease decreases the residual oil saturation and consequently increases the oil recovery.

8. Higher salt concentration gave lower reduction in the IFT values between crude oil and nutrient solution, lower reduction in the pH of the nutrient solution, and lower increase in the viscosity of the aqueous phase.
9. In the presence or absence of molasses, no clear trend of absolute permeability on oil-water relative permeability curves was observed.
10. From the relative permeability curves, the rock wettability characteristics can be identified.

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TABLE 1- SUMMARY OF THE RELATIVE PERMEABILITY TESTS

Test No.	Core sample No.	Absolute Permeability, md.	Crude oil Type	Initial water Salinity, %NaCl	Molasses Concentration, %
1	4	1550	A	4	0
2	4	1550	A	4	0
3	1	266	A	4	0
4	1	266	A	4	1
5	2	872	A	4	0
6	2	872	A	4	1
7	1	266	B	4	1
8	2	872	A	15	1
9	2	872	A	20	1
10	3	666	A	4	0
11	3	666	A	4	1
12	4	1550	A	4	1

TABLE 2- QUANTITATIVE ANALYSES - EFFECT OF MOLASSES CONCENTRATION

Core Sample	Crude Oil	Molasses Concentration					
		0.0 % Molasses			1.0 % Molasses		
		S_w@ Kro=Krw , %	S_{or} , %	Recovery , %	S_w@ Kro=Krw , %	S_{or} , %	Recovery , %
1	A	48.50	22.80	69.60	58.5	18.50	75.30
2	A	55.00	29.80	60.30	60.00	24.50	67.30
1	B	48.50	22.80	69.60	55.50	18.90	74.80

TABLE 3- AQUEOUS PHASE PROPERTIES MEASUREMENTS AT DIFFERENT MOLASSES CONCENTRATIONS FOR CRUDE OILS A AND B

Property	Crude Oil	Molasses Concentration		
		0.0 % Molasses	1.0 % Molasses	
			0.0 hrs. Incubation Time	48.0 hrs. Incubation Time
IFT, mN/m	A	30.0	27.5	16.0
	B	31.0	29.0	19.0
Viscosity of aqueous phase, cp	A	1.003	1.07	1.39
	B	1.003	1.07	1.31
pH of aqueous phase	A	6.85	6.81	5.40
	B	6.85	6.81	5.80

TABLE 4- QUANTITATIVE ANALYSES- EFFECT OF SALINITY

Formation Water Salinity	S_w@ Kro=Krw , %	S_{or} , %	Recovery , %
4% NaCl	60.00	24.0	67.3
15% NaCl	58.00	25.2	66.4
20% NaCl	55.2	25.2	66.4

TABLE 5- AQUEOUS PHASE PROPERTIES MEASUREMENTS AT DIFFERENT FORMATION WATER SALINITY FOR CRUDE OIL A WITH 1% MOLASSES

Property	Formation Water Salinity					
	4 % NaCl		15 % NaCl		20 % NaCl	
	0.0 hrs. Incubation Time	48.0 hrs. Incubation Time	0.0 hrs. Incubation Time	48.0 hrs. Incubation Time	0.0 hrs. Incubation Time	48.0 hrs. Incubation Time
IFT, mN/m	27.5	16.0	27.0	21.0	27.0	22.0
Viscosity of Aqueous Phase, cp	1.07	1.39	1.10	1.33	1.16	1.30
pH of Aqueous Phase	6.81	5.40	6.60	6.40	6.60	6.50

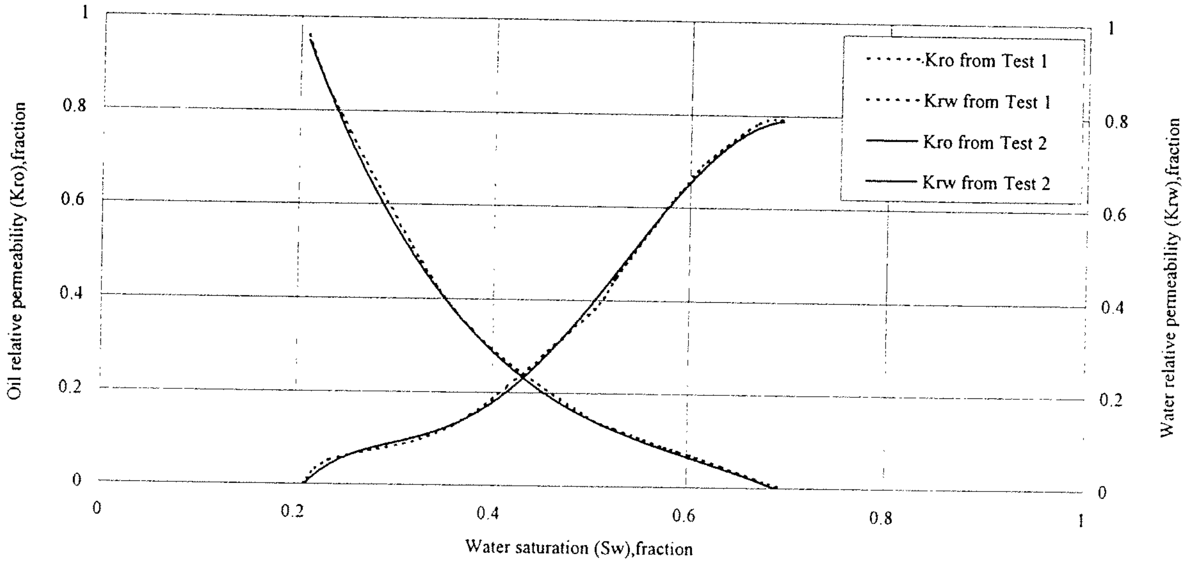

Fig. 1- Water-oil relative permeability curve of Sample 4 using Crude Oil A and 4% NaCl formation water salinity with 0% molasses concentration at 40 °C (Two tests).

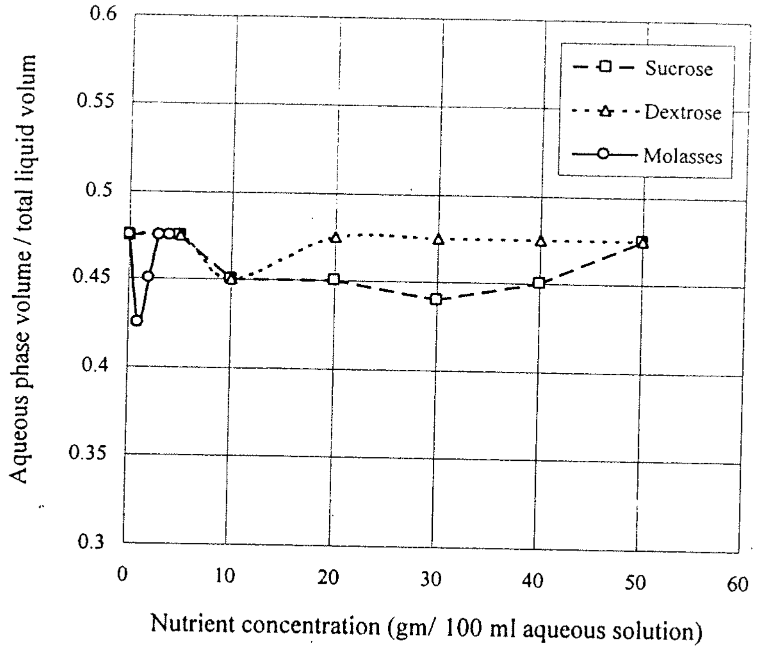

Fig. 2-Effect of nutrient type and concentration on phase volume with Crude Oil A after two days using 4% NaCl at 40 °C.

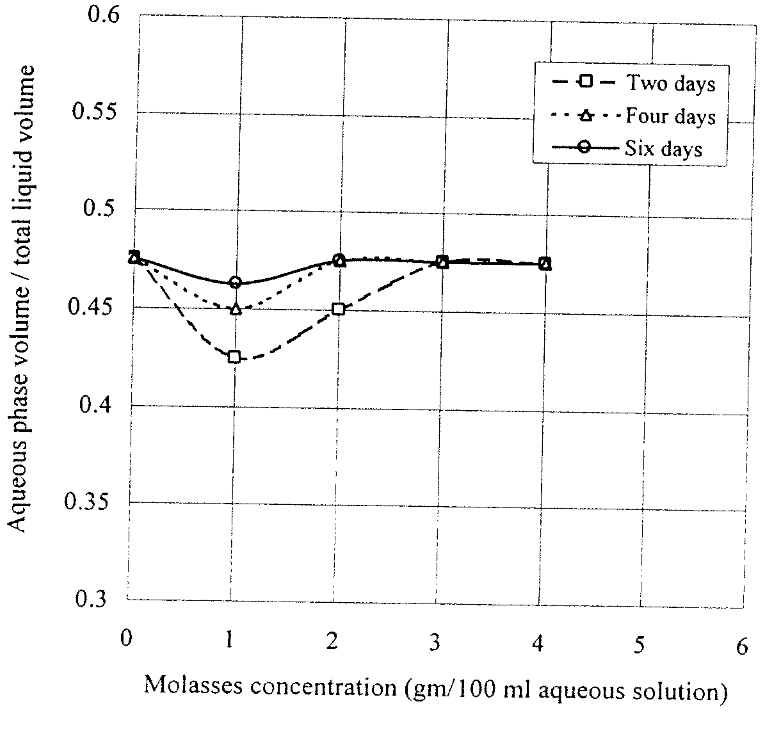

Fig. 3-Effect of incubation time and concentration on phase volume for molasses and Crude Oil A using 4% NaCl at 40 °C.

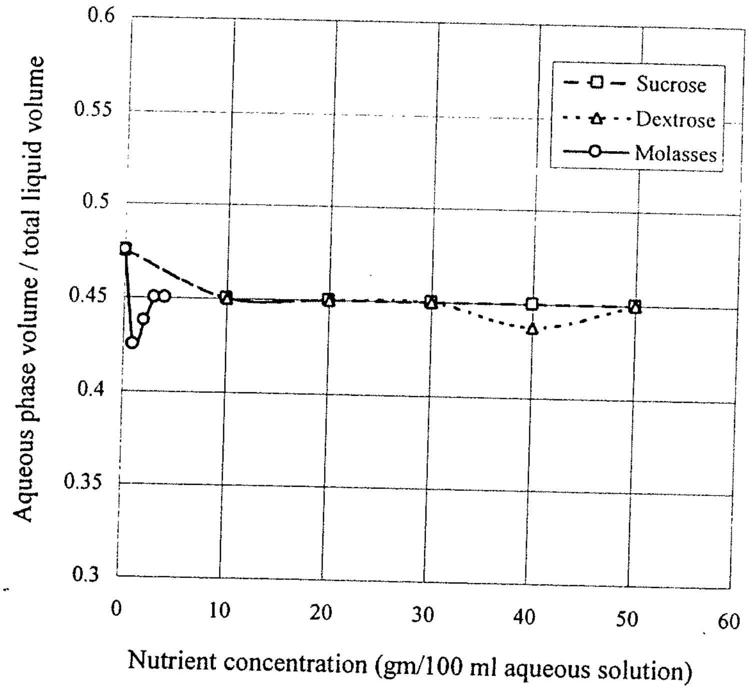

Fig. 4-Effect of nutrient type and concentration on phase volume with crude oil B after two days using 4% NaCl at 40 °C.

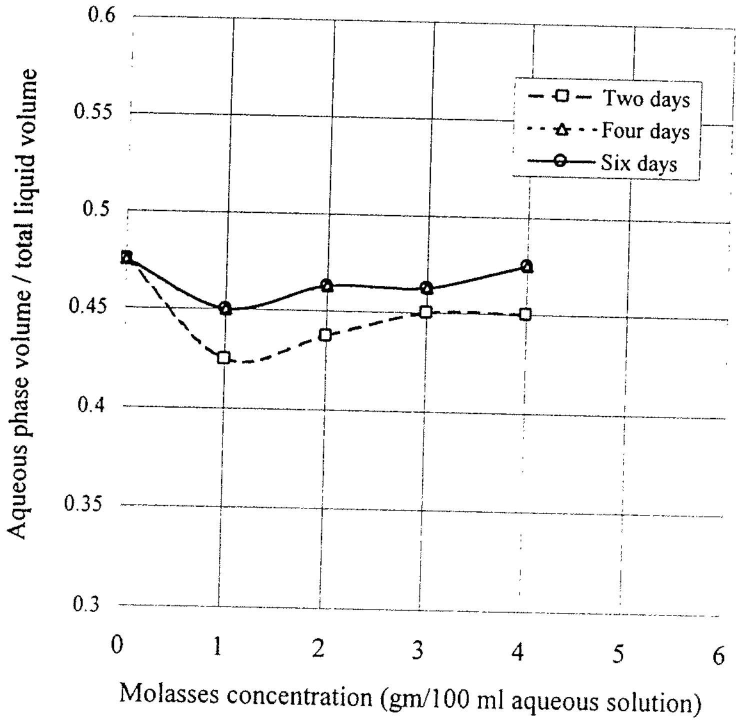

Fig. 5-Effect of incubation time and concentration on phase volume for molasses and crude oil B using 4% NaCl at 40°C.

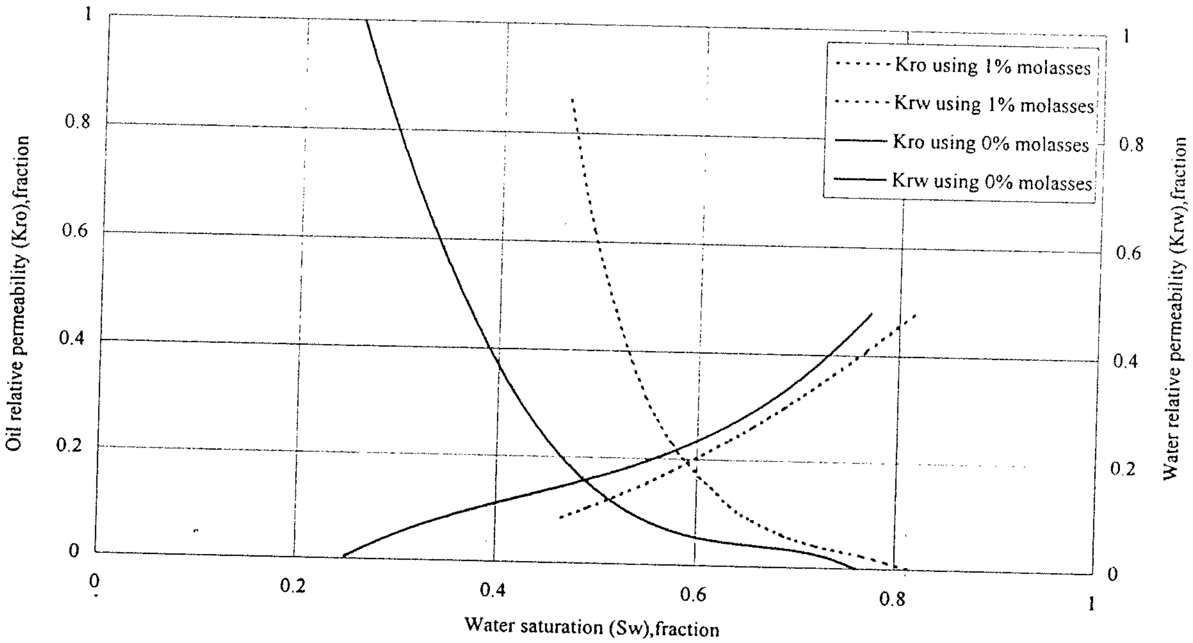

Fig. 6- Effect of molasses concentration on water-oil relative permeability curve of Sample 1 using Crude Oil A and 4% NaCl formation water salinity after two days incubation time at 40 °C.

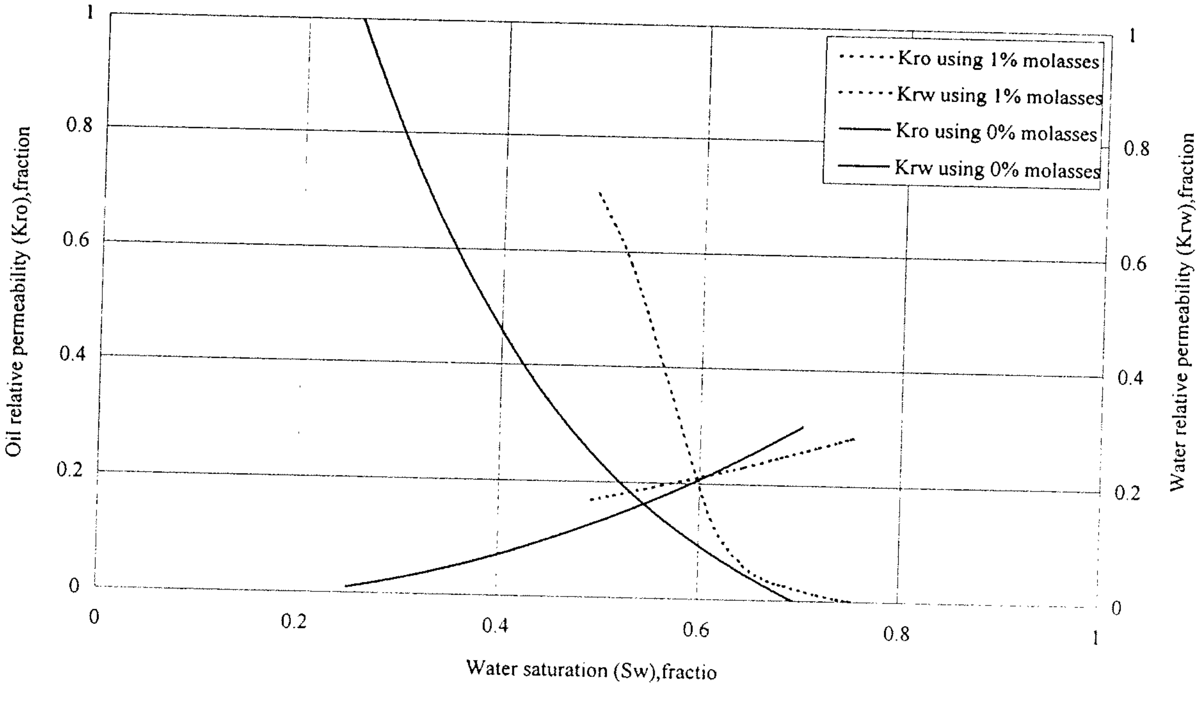

Fig. 7- Effect of molasses concentration on water-oil relative permeability curve of Sample 2 using Crude Oil A and 4% NaCl formation water salinity after two days incubation time at 40 °C.

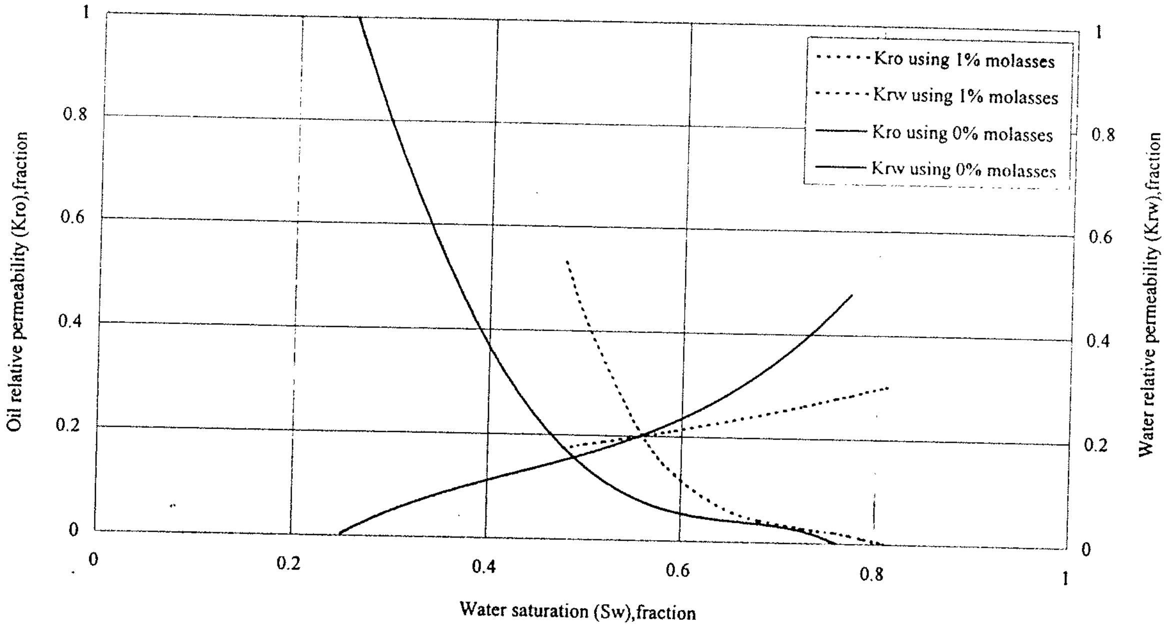

Fig. 8- Effect of molasses concentration on water-oil relative permeability curve of Sample 1 using Crude Oil B and 4% NaCl formation water salinity after two days incubation time at 40 °C.

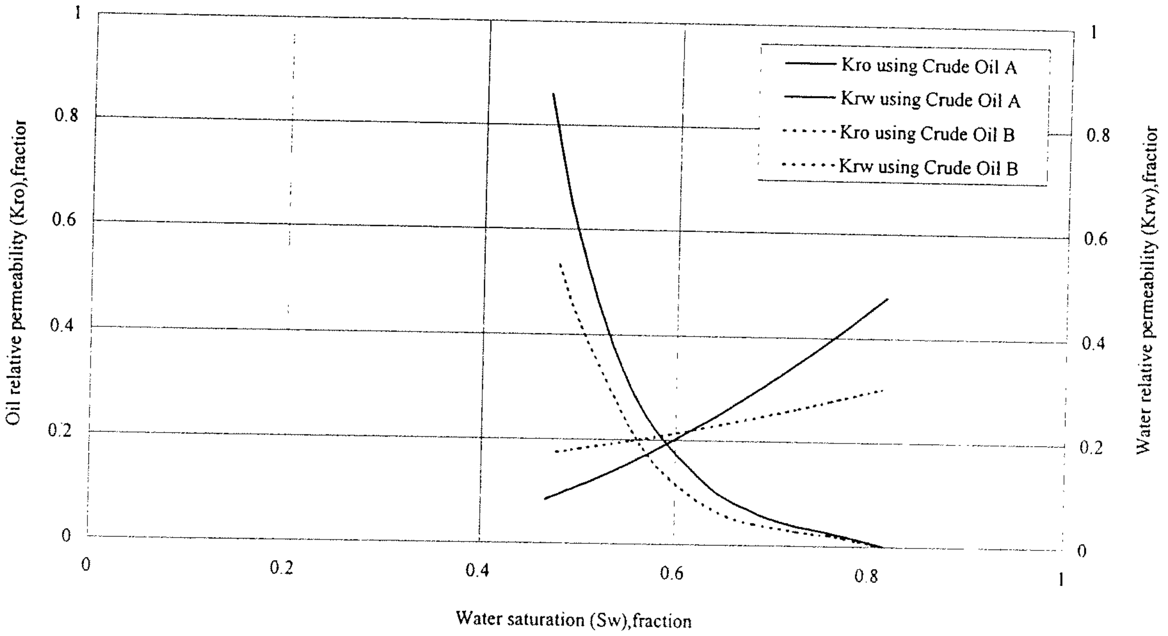

Fig. 9- Effect of crude oil type on water-oil relative permeability curve of Sample 1 using 1% molasses concentration and 4% NaCl formation water salinity after two days incubation time at 40 °C.

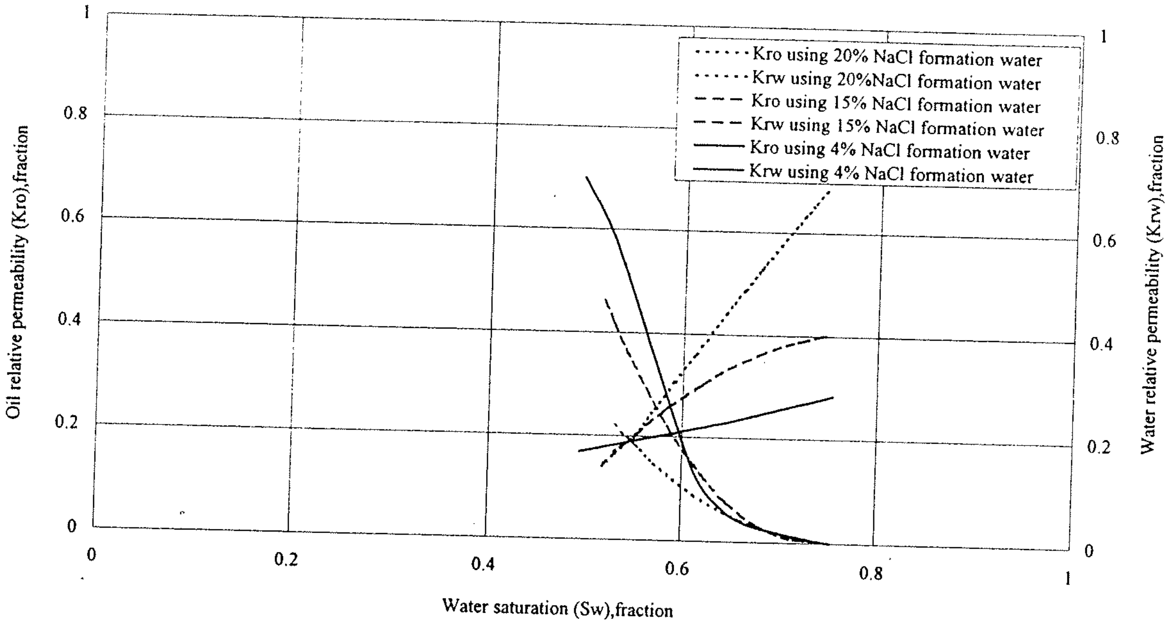

Fig. 10- Effect of formation water salinity on water-oil relative permeability curve of Sample 2 using Crude Oil A with 1% molasses after two days incubation time at 40 °C.

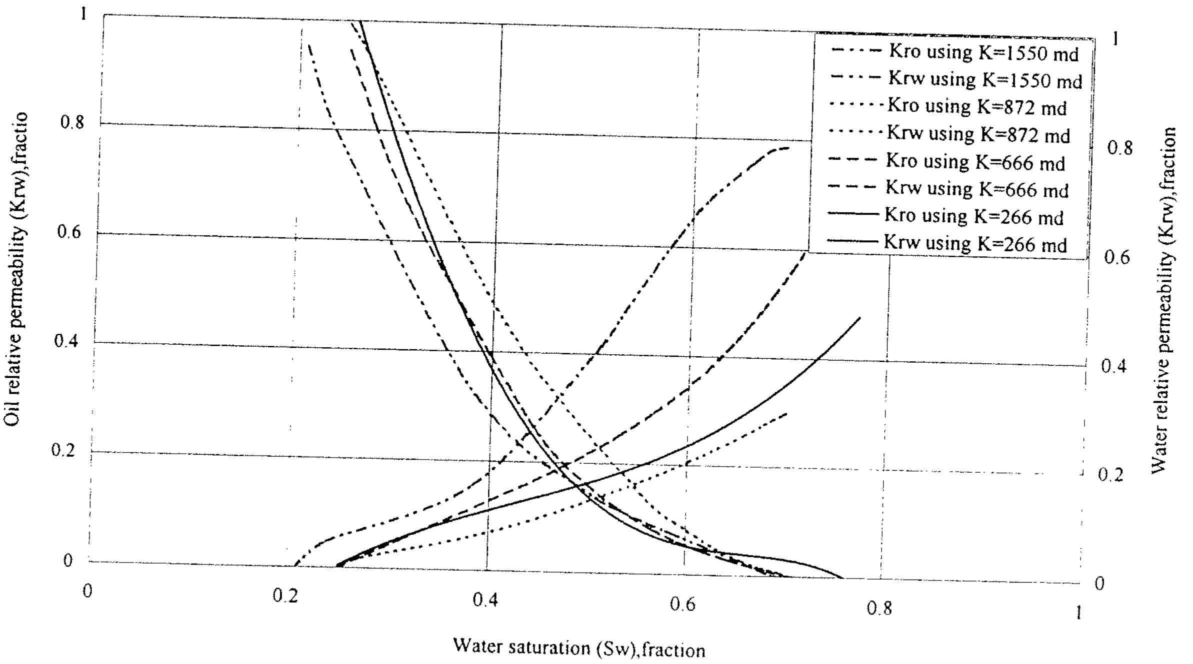

Fig. 11- Effect of absolute permeability on water-oil relative permeability curve using 0% molasses concentration with Crude Oil A and 4% NaCl formation water salinity at 40 °C.

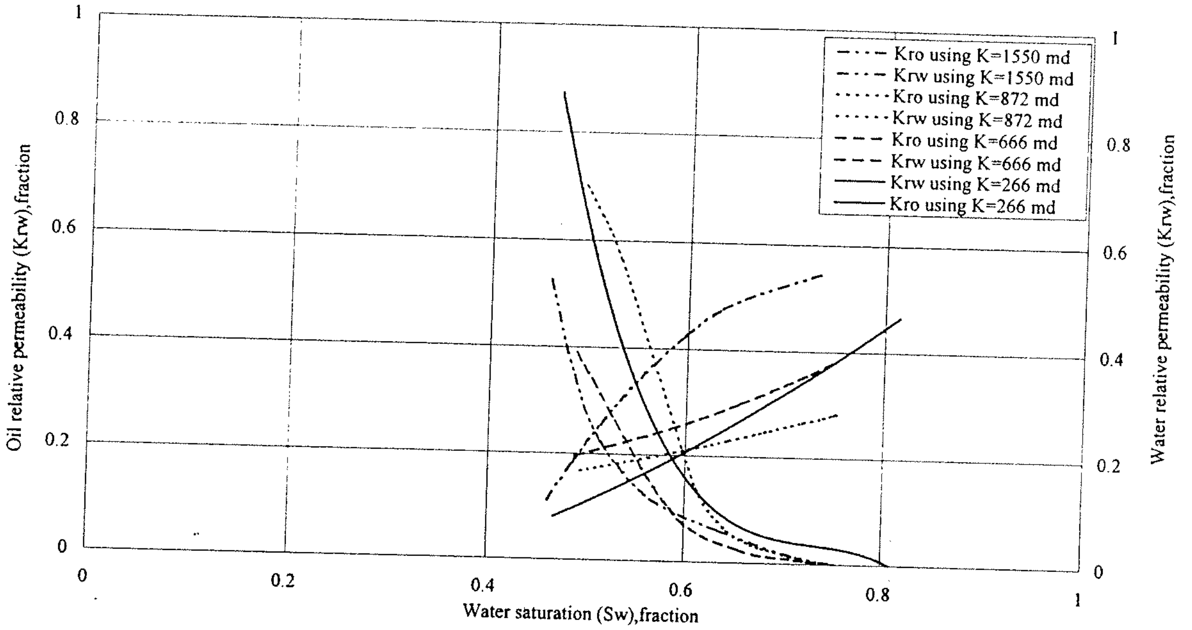

Fig. 12-Effect of absolute permeability on water-oil relative permeability curve using 1% molasses concentration with Crude Oil A and 4% NaCl formation water salinity after two days incubation time at 40°C.