WETTABILITY AND PREDICTION OF OIL RECOVERY FROM RESERVOIRS DEVELOPED WITH MODERN DRILLING AND COMPLETION FLUIDS

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Disclaimer

Project Objectives

The objectives of this project are:

1. to improve understanding of the wettability alteration of mixed-wet rocks that results from contact with the components of synthetic oil-based drilling and completion fluids formulated to meet the needs of arctic drilling;

2. to investigate cleaning methods to reverse the wettability alteration of mixed-wet cores caused by contact with these SBM components; and

3. to develop new approaches to restoration of wetting that will permit the use of cores drilled with SBM formulations for valid studies of reservoir properties.

Abstract

This report summarizes the experimental results of some baseline imbibition tests on recovery of mineral oil at very strongly water wet conditions (VSWW) from sandstones with air permeability ranging from 80 to 360 md. Mixed wettability cores were prepared by adsorption from either Minnelusa or Gullfaks crude oil using either synthetic Minnelusa reservoir brine or sea water. Recovery of two synthetic-based mud (SBM) base oils, Petrofree®SF and LVT 200 from mixed wettability cores gave results that correlated closely with results for refined oils with viscosities ranging from 3.8 to 84 cp. Two synthetic-based mud emulsifiers (LE SUPERMUL and EZ MUL®NT) were added to mineral oil and tested for their effect on the wettability of MXW-F core samples as indicated by spontaneous imbibition. In both cases a significant decrease in water wetness was obtained.

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Baseline Core Imbibition Studies

YongSheng Zhang, ZhengXin Tong and N.R. Morrow

1. Introduction

Drilling muds are employed to carry away drilled cuttings, cool and lubricate drill bits and maintain well bore pressure. Three major types of drilling muds are used in the oil and gas industry: water-based muds (WBMs), oil-based muds (OBMs) and synthetic-based muds (SBMs). OBMs are preferred over WBMs under certain circumstances but the drilled cuttings from OBM are toxic to the environment. Growing environmental issues and government regulations restrict the use of OBMs and result in the increasing application of environmentally friendly SBMs. However, laboratory core tests show that SBM, as for OBMs, can cause drastic change in wettability. Change in rock wettability impacts two-phase displacement parameters such as residual oil saturation, relative permeability and capillary pressure and causes great uncertainty in estimates of oil recovery by waterflooding.

This research is aimed at improved fundamental understanding of the wettability alteration of mixed-wet rocks resulting from contact with the components of SBMs. The study will include investigation of cleaning methods designed to reverse the wettability alteration of mixed-wet cores caused by contact with these SBM components. Restoration of the cleaned cores to the original reservoir wettability will permit valid studies of reservoir properties using cores drilled with SBM formulations.

It is increasingly believed that the wetting conditions of most hydrocarbon reservoirs are mixed-wet (MXW). The MXW state is formed by adsorption of polar crude oil components onto rock surfaces in the presence of initial formation water. MXW cores can be prepared for laboratory study by aging core samples with initial water saturation in crude oil. MXW (film) cores (MXW-F) can be prepared by displacing the crude oil in MXW cores with decalin followed by injection of mineral oil (Tong et al., 2002a, b, and c). Displacement tests are then usually run with a refined mineral oil as the probe oil. This report includes comparison of the wetting behavior of MXW and MXW-F cores. Preliminary results on the interaction of MXW-F cores with surface active components in SBMs are also presented.

2. Experimental

2.1 Cores

Many oil recovery studies over the past 50 years have been made with a Berea sandstone of about 500 md supplied by Cleveland Quarries. Results for this rock are designated Berea 500. Presently rock ordered from this quarry has been in the range of 60 to 120md. Other Berea samples on hand in our laboratory and some blocks supplied by industry provide a wider range of permeability but still show distinct differences in properties to the Berea 500. Sandstones currently available for use in this project are listed in Table 1. Clay mineral types from x-ray analysis, BET surface areas, and cation exchange capacities, are being determined for each rock. Results obtained to date are summarized in Table 2. Basic petrophysical properties of the cores used in imbibition tests are included in Table 3.

Table 1 Available Berea sandstones*

Block	Dimension, in	k, md	ϕ, %
EV1	$12 \times 12 \times 16$	~90	~17
EV2	$12 \times 12 \times 16$	~90	~17
EV3	$12 \times 12 \times 16$	~90	~17
EV4	$12 \times 12 \times 16$	180 ~ 360	18~20
EV5	$12 \times 12 \times 16$	~250	~18
EV6	$12 \times 12 \times 16$	~200	~18
EV7	$12 \times 12 \times 16$	~100	~18
EV8	$12 \times 12 \times 16$	~90	~17.5
C1	$12 \times 12 \times 6$		
C2	$12 \times 12 \times 6$	~70	~17
C3	$12 \times 12 \times 6$		
C4	$12 \times 12 \times 6$		
C5	$12 \times 12 \times 6$		
Ph2	$11.5 \times 11.5 \times 12$	~700	~22
Ph5	$11.5 \times 11.5 \times 12$	~200	

* Supplied by Cleveland Quarries, Ohio.

Table 2 Sandstone properties

Core	k_g, md	Clay minerals	BET,m^2/g	CEC,meq/100g
B90	90	Kaolinite = Illite > Chlorite	0.935	0.00284
Ph1	640	Kaolinite = Illite > Chlorite	0.838	0.00197
Ph1	1050	Kaolinite > Illite > Chlorite	0.673	0.00140
Ph3	1100	Kaolinite > Illite > Chlorite	0.551	0.00174

Table 3 Properties of core samples used in spontaneous imbibition tests

Core	k_g md	ϕ %	S_{wi} %	T_f °C	Status	R^1_{im}, %OOIP	R_{wf} %OOIP	I_w	I_o
EV4-1	254	19.5	26	21	Mineral oil	42.1	42.1	1	0
EV4-2	187	18.8	26.8	40	M'02 MXW-F [2]	7.7	70.8	0.12	0.12
EV4-3	189	18.9	26.8	40	M'02 MXW	20	i.p.[3]		
EV4-4	194	19.1	26.4	21	Gullfaks MXW	40.6	44.5	0.65	0
EV4-5	177	18.7	26.7	21	Gullfaks MXW-F	46	50.3	0.90	0
EV4-6	188	18.9	0	n/a	Soltrol 220	48		1[4]	0[4]
EV4-7	357	20	0	n/a	Soltrol 220	46.9		1[4]	0[4]
5B19	81	17.6	25.4	45	Gullfaks MXW	37.1			
5B22	90	18.3	25.9	45	Gullfaks MXW	33.5			
5B23	81	17.7	25.8	45	Gullfaks MXW-F	36.6			
5B25	106	18.6	26.2	45	Gullfaks MXW-F	39.7			
5B2	93	17.9	24.6	50	M'98 MXW	32			
5B8	104	18.5	24.6	50	M'98 MXW	35.5			
5B3	98	18	25	50	M'98 MXW-F	12.5			
5B7	105	18.3	24.6	50	M'98 MXW-F	14.2			
3B14a	106	18.7	27.1	50	M'02 MXW-F	20			
2BV3	149	18.9	25	50	M'02 MXW-F	20			
3B5	94	18.2	26.1	50	M'98 MXW-F	14			

1 The oil recoveries correspond to dimensionless time of 20,000.
2 M stands for Minnelusa.
3 Imbibition test is still in progress.
4 Assumed values.

2.2 Oils

Soltrol 220 (3.8 cp) and mixtures of Soltrol 220 and a viscous mineral oil (180 cp), were used in VSWW tests and as probe oils for mixed wet cores (see Table 4). These refined oils were rendered free of polar impurities by exposure to alumina and silica gel.

Two base oils used in the formulation of SBMs, Petrofree®SF and LVT 200, were tested as supplied by the mud company. Their compositions and physical properties are summarized in Table 4.

A list of crude oils and the quantity currently available are listed in Table 5. Properties, measured to date, of the crude oils used to prepare mixed wet cores are included in Table 5. Crude oils used in the present work are designated as Minnelusa'98, Minnelusa'02, and Gullfaks (see Table 5). All of the crude oils were filtered to remove solid particulates. Minnelusa'98 oil was vacuumed at ambient temperature for 1 hour before use to reduce its volatility.
Unlike the Minnelusa 98 sample the Minnelusa'02 oil contained a large fraction of emulsified brine at the time of sampling. This was probably the result of a slipping pump rather than any drastic change in the basic properties of the produced oil. Density measurements indicated that the oil contained about 50% brine. The brine slowly segregated from the oil. The density of the oil sampled from top of the sample decreased from 0.9112 g/cc to 0.9042 g/cc @ 20°C when the storage time increased from five months to ten months.

Table 4 Properties of mineral oils and SBM base oils

Properties \ Oil	LVT 200	Petrofree® SF	Soltrol 220	Mineral oil (extra heavy)
Density at 20°C, g/cc	0.8162	0.7834	0.7833	0.8712
Viscosity at 20°C, cp	2.9	3.4	3.8	180
RI at 20 °C	1.4503	1.4445	1.4357	
Composition	Cycloparaffinic, isoparaffinic, and normal paraffinic hydrocarbons, >99 wt. %	Isomerized olefins, 60~100 wt. %	C13 ~ C16 isoalkanes, 100 wt. %	~

Table 5 Available crude oils

Crude oil I.D.	Amount (gallon)	Date obtained	Source	ρ, g/cc (20°C)	μ_o @25°C	nC7-asph, wt.%	Acid no.	Base no.
Minnelusa'98	6	1998	Gibbs, Wyoming	0.9051	43.6	8.98	0.17	2.29
Minnelusa'02	42	5/02	Gibbs, Wyoming	0.9042			0.01	2.01
Gullfaks	26	4/02	Norway	0.8806	12.3	0.4	0.24	1.19
CS	4	-	U.K.	0.9036	61.4	0.78	0.33	1.16
DaGang	10	07/94	Dagang, China	0.8883	solid	6.3	0.66	4.67
Lloyd	5			0.9482			0.2	2.67
Monument Butte	3	2002	Utah		solid		0.08	0.99
Ladybug	42	03/03						
Fuji W#3	37	03/03		~0.88*		~11*		
McElroy	42	11/03		~0.88*		~2*	~0.2*	~1*
Tensleep	30	4/95		0.8684	21.6	3.2	0.16	0.96
Cottonwood	35	04/02		0.8960		2.3	0.56	1.83

* Values marked have not yet been measured for the samples on hand, but are those measured using different samples from these fields.

Table 6 Brine compositions

Brine	ρ @ 20°C	Ionic compositions, ppm							
		K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	SO_4^{2-}	TDS
Minnelusa	1.0277	-	13,625	760	170	19,424	-	4,664	38,653
Sea water	1.0231	490	11,010	430	1,360	22,176	-	-	35,466

Table 7 SBM components on hand

Trade name	application	Specific gravity @20°C	Viscosity @20°C, cp	Compositional information from MSDS*
EZ MUL®NT	emulsifier	0.96	0.924	Ethylene glycol monobutyl ether, 1 ~ 5 wt.% Diethylene glycol monobutyl ether, 1 ~ 5 wt. % Hydrotreated light petroleum distillate, 10 ~ 30 wt. %
LE SUPERMUL	emulsifier	0.92	280 ~ 300	Ethylene glycol monobutyl ether, 1 ~ 5 wt. % Diethylene glycol monobutyl ether, 1 ~ 5 wt.%
LE MUL	emulsifier	0.92	1550~1750	Ethylene glycol monobutyl ether, 1 ~ 5 wt.% Diethylene glycol monobutyl ether, 1 ~ 5 wt.%
INVERMUL® NT	emulsifier	0.92~0.95	430	Hydrotreated light petroleum distillate, 10 ~ 30 wt.% Ethylene glycol monobutyl ether, 1~5 wt. % Diethylene glycol monobutyl ether, 1~5 wt. %
DEEP-TREAT	thinner	1.5	n/a (powder)	Sulfonic acid salt, >90wt.%
BAROID®	weight additive	4.2	n/a (solid)	Barium sulfate, 60~100 wt.%; Crystalline silica, quartz, 1~5 wt. %
DURATONE® HT	fluid loss additive	1.8	n/a (solid)	Crystalline silica, quartz, 1~5wt.%; Nonylphenol, 5~10 wt.% Lignite, 30~60 wt.%; Quaternary ammonium compounds, 10~30 wt.%
GELTONE® II	viscosifier	1.6	n/a (powder)	Bentonite, 30~60wt.%; Crystalline silica, quartz, 1~5wt.%; Quaternary ammonium compounds, 30~60wt.%; Crystalline silica, cristobalte, 0~1wt.%; Crystalline silica, tridymite, 0~1 wt.%

* In most cases this information is incomplete and may omit some active ingredients.

2.3 Brines

Synthetic Minnelusa reservoir brine and synthetic sea water were formulated using the chemical compositions provided for the original reservoir brines shown in Table 6. Sodium azide (NaN_3) was added (100 ppm) to the brines to prevent bacterial growth. The brines were evacuated just before use in order to remove dissolved gas.

2.4 Synthetic-based mud emulsifiers

Physical properties and compositions of eight SBM components on hand are summarized in Table 7. Two kinds of synthetic-based mud emulsifiers, EZ MUL®NT and LE SUPERMUL, were used to investigate their effects on oil/brine/rock interactions.

2.5 Establishing S_{wi}, aging and preparation of MXW-F cores

Cores from EV4-1 through EV4-5 were first vacuumed and saturated with Minnelusa reservoir brine and aged in the same brine at 75°C for 10 days to reach ionic equilibrium. EV4-1, EV4-4 and EV4-5 were flushed with a 90 cp mineral oil at an injection rate of 0.5 to 3 ml/min at room temperature to achieve the desired S_{wi}'s. The 90 cp mineral oil in EV4-1 was then displaced by Soltrol 220 before running VSWW spontaneous imbibition tests at Swi of 26%. The 90 cp mineral oil in EV4-4 and EV4-5 was displaced with 5 PV of decalin (0.5 ~ 2 ml/min) which was in turn displaced by 5 PV of Gullfaks crude oil. EV4-2 and EV4-3 were flushed with

Minnelusa'02 crude oil at 40°C to establish S_{wi}. Initial water saturations for all these cores are about 27 % (see Table 3).
The cores EV4-2 ~ EV4-5 containing crude oil were aged for10 days in sealed stainless steel cells at 75°C. The MXW cores, EV4-3 and EV4-5, were allowed to cool for about 5 hours and then placed in graduated glass imbibition cells filled with Minnelusa reservoir brine. MXW-F cores were prepared by displacing the crude oil in cores EV4-2 and EV4-5 with 5 PV of decalin ($C_{10}H_{18}$, decahydronaphthalene, perhydronaphthalene) at a flow rate of 0.5 ~ 2cc/min. The decalin was displaced by 5 PV of Soltrol 220 at room temperature.

For the other cores listed in Table 3, brine was displaced either with Minnelusa crude at 50°C or Gullfaks crude at 40°C at a flow rate of 0.2 m/min to 5.0 ml/min to establish S_{wi}. After 10 days' aging at T_a 7(5°C), crude oil was displaced by 5 PV of decalin at 3 ft/day (about 0.72 PV/hr). The decalin flush temperature, T_f, was 50°C for Minnelusa treated cores and 40°C for Gullfaks treated cores. Decalin was then displaced with 5 PV of mineral oil of selected viscosity at ambient temperature (21°C).

Temperature of measurement, T_m, for recovery of mineral oil by spontaneous imbibition was ambient for all tests.

2.6 Spontaneous imbibition

For some of the cores, imbibition was essentially complete after about 8 days, but for some of the mixed wet cores the spontaneous imbibition still continued even after more than 1 month. Results are presented as recovery vs. dimensionless time in Figs.1 to 9 where the dimensionless time is calculated using the following equation (Ma, et al, 1995):

$$t_D = t\sqrt{\frac{k}{\phi}}\frac{\sigma}{\sqrt{\mu_o\mu_w}}\frac{1}{L_c^{\,2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where L_c is a characteristic length that compensates for sample size, shape and boundary conditions; k is absolute permeability (md); σ is the oil/brine interfacial tension (mN/m); μ_o is the viscosity to oil (cp); μ_w is the viscosity to brine (cp); ϕ is the porosity of rock sample and t is the imbibition time (min).

2.7 Amott wettability index

Amott wettability indices to water and oil were measured. After spontaneous imbibition the core was set in a core holder and the additional oil recovery was given by forced displacement at 0.5 cc/min. As a check on determining that a robust residual oil had been achieved the flow rate was increased in steps to 1.0cc/min, 2.0cc/min and then 3.0 cc/min. If oil continued to be produced after the flow rate had been increased to 3.00 cc/min, the recovery after injection of 3 PV at this rate was used as the forced imbibition end point. The Amott index to water was calculated using the following equation:

$$I_w = \frac{V_{oi}}{V_{oi} + V_{of}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

The Amott wettability index to oil was measured from spontaneous and forced imbibition of oil and calculated using equation 3.

$$I_o = \frac{V_{wi}}{V_{wf} + V_{wi}} \quad \text{……………………………} (3)$$

Amott wettability index, I_{Amott}, is $I_w - I_o$. Cuiec (1990) suggested the classification of wettability from the Amott index shown in Table 9.

Table 9 Wettability Index and Wettability

I_{Amott}	-1	-0.3	-0.1	+0.1	+0.3 +1
wettability	oil wet	slightly oil wet	neutral	slightly water wet	water wet

For the values of I_w included in Table 3, oil production by spontaneous imbibition had essentially ceased.

3. Results and Discussion

3.1 Reference curves for VSWW imbibition

The reference curve designated as Berea 250, S_{wi} = 0% in Fig.1 was obtained based on the imbibition test results from two VSWW cores without initial water. The oil recovery associated with this reference curve was calculated using the following equation (Aronofsky et al., 1958):

$$R = R_o(1 - e^{-\alpha t_D}) \quad \text{……………………………….. } (4)$$

where $\alpha = 0.01881$ for the adopted experimental conditions and the tested core samples. The other reference curve designated as Berea 250 S_{wi} = 26 % is also presented in Fig. 1 for comparison. An imbibition test was performed on this core (EV4-1) with an initial water saturation of of 26 %. The Soltrol 220 /brine/ rock system for EV4-1 gave an Amott wettability index of 1, as expected. Oil recovery reached almost 40% OOIP within 1 hour and increased by only 2% thereafter. Although the wetting conditions associated with both curves shown in this figure correspond to very strongly water-wet condition, compared to Berea 250, S_{wi} = 0 % reference curve, the Berea 250 S_{wi} = 26% shows a shift toward slightly reduced rate and recovery. The reduction in rate with the presence of initial water saturation is consistent with measurements for Berea 500 reported by Viksund et al (1998).

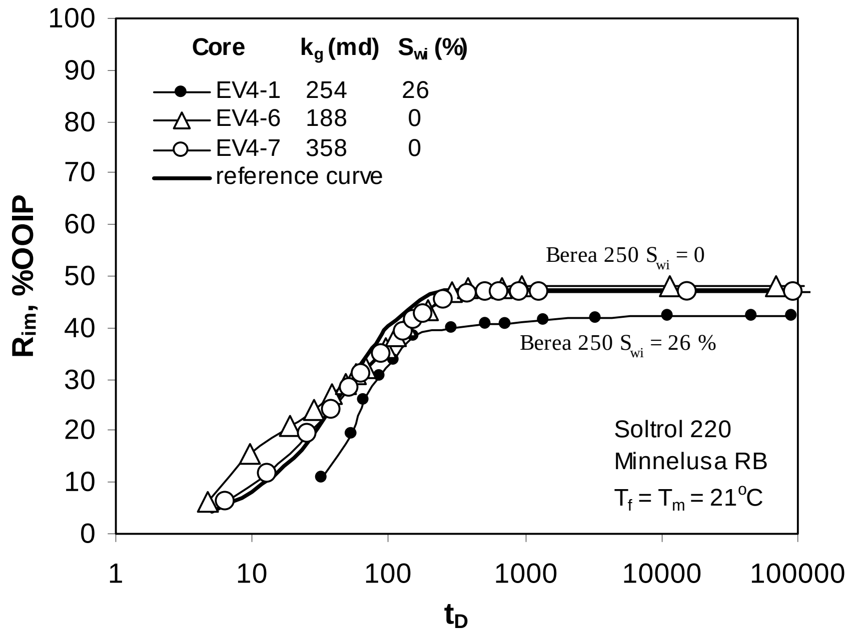

Figure 1. Spontaneous imbibition characteristics for very strongly water-wet cores with 0 % and 26 % initial water saturation.

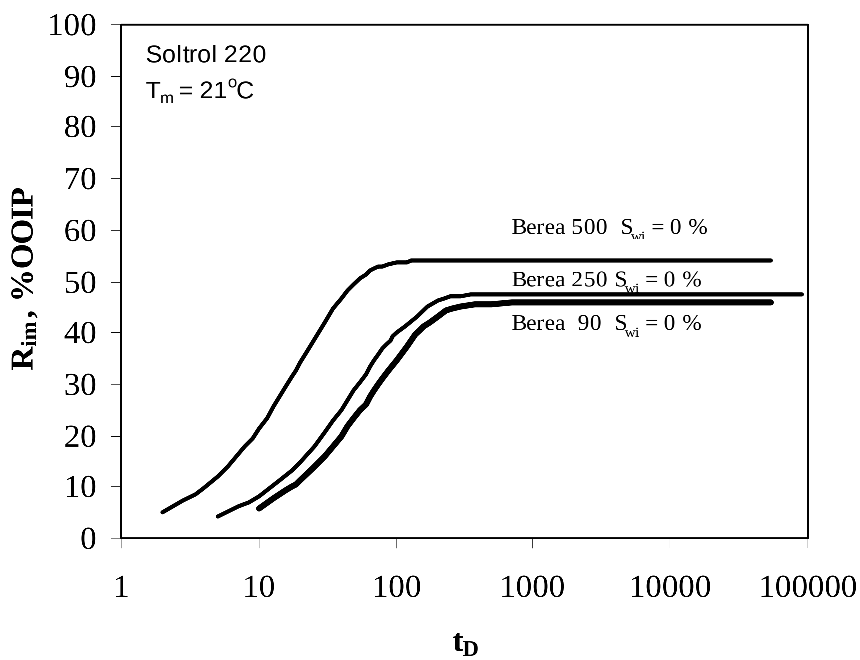

Figure 2. R_{im} vs. t_D for cores with different permeability at S_{wi} = 0%

Fig.2 compares the three reference curves based on the cores with permeability of about 90, 250 and 500 md. These curves are designated as Berea 90, Berea 250 and Berea 500 respectively. The Berea 500 reference curve is well separated from the curves for Berea 90 and Berea 250. However, the Berea 500 result agrees with a wide range of other rock types and synthetic materials (Viksund et al., 1998).

3.2 MXW and MXW-F results

3.2.1 Gullfaks oil

Imbibition rates for the Gullfaks core were initially slower than for the Berea 250, Swi = 0 % , reference curve and for the Berea 250, Swi = 26 % curve (see Fig.3). At the late stage of imbibition, recovery from the MXW-F core was higher than for the VSWW cores. The small wettability change observed for the Gullfaks oil is consistent with previous observations (Tong et al., 2002b).

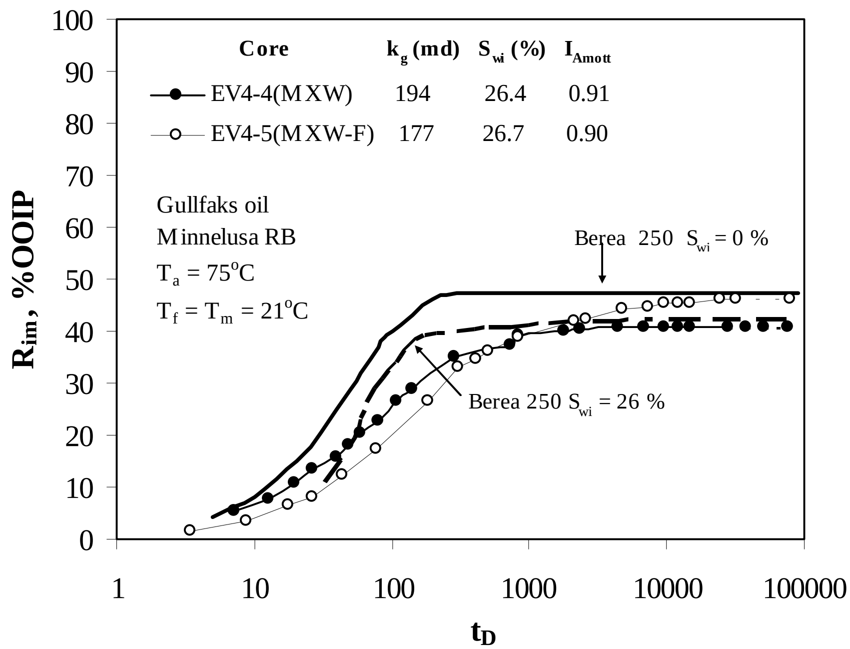

Figure 3. Comparison of spontaneous imbibition characteristics between Gullfaks MXW and MXW-F Berea 250 cores.

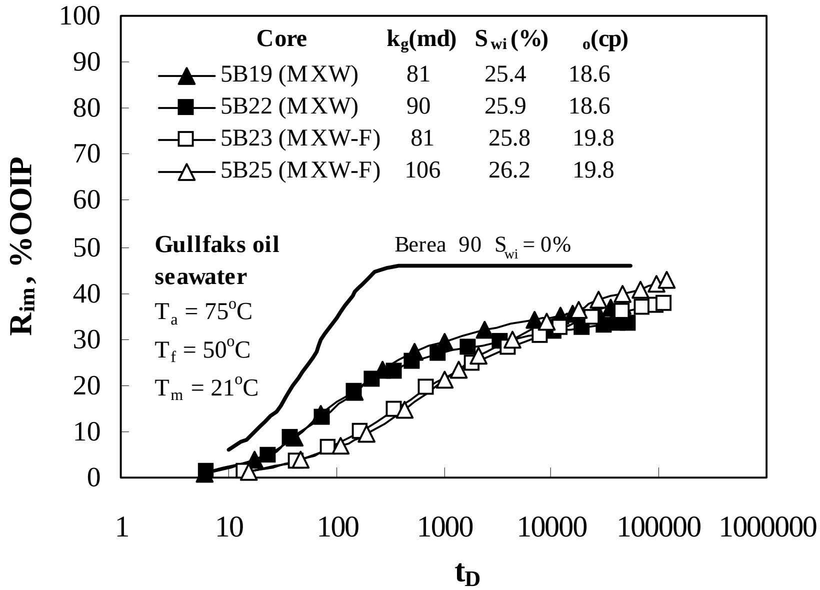

Figure 4. Comparison between Gullfaks MXW and MXW-F Berea 90 cores.

Fig. 4 shows the imbibition characteristics for duplicate tests of Gullfaks MXW and MXW-F cores. The two curves for either MXW or MXW-F cores show good reproducibility.

The scaled imbibition curves in Fig.4 are comparable to those shown in Fig.3. Both sets of tests show a crossover between the imbibition curves for MXW-F and MXW cores at the late stage of imbibition. After about 8 days' imbibition, the cores EV4-4 and EV4-5 (see Fig.3) showed cessation of oil production, but the cores presented in Fig.4 showed slow continued production of oil.

3.3 Minnelusa oil

Imbibition characteristics for cores prepared with Minnelusa '02 are shown in Fig. 5. Imbibition rates for the Minnelusa oil prepared cores were much slower than for the cores treated with Gullfaks oil. The Amott wettability index for EV4-2 is 0.

The cores used to obtain the results shown in Fig. 6 were from a different block of Berea sandstone and treated using Minnelusa'98 oil. The imbibition results give close reproducibility and are qualitatively similar to the comparison of MXW and MXW-F results shown in Fig.5. Both sets of tests indicate that MXW cores have higher imbibition rate than for MXW-F cores.

Fig.7 shows a comparison of MXW-F cores for Minnelusa'98 oil and Minnelusa'02 oil. The dotted line is an average result obtained from the three MXW-F curves shown in Fig.6. The MXW-F cores prepared using Minnelusa'02 oil have a slightly higher imbibition rate than the MXW-F cores prepared with Minnelusa'98 oil.

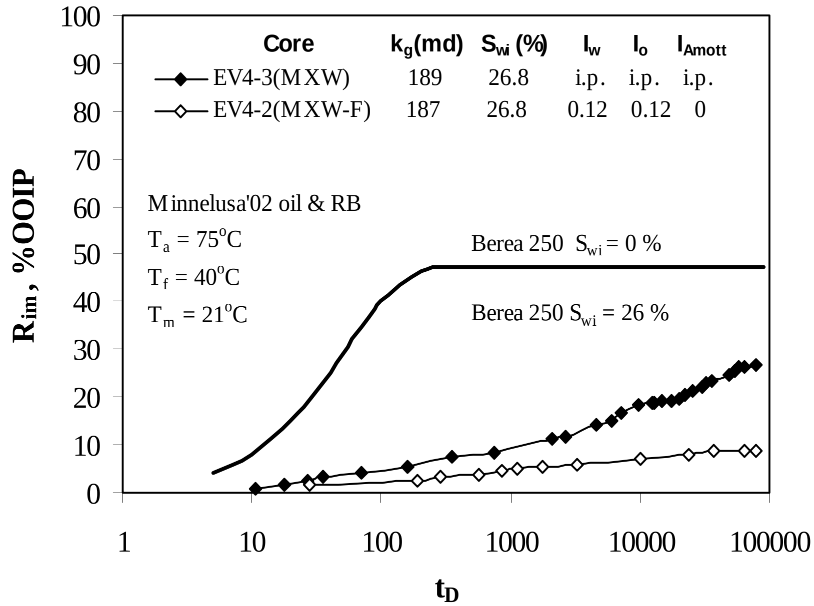

Figure 5. Comparison of imbibition rates between Minnelusa '02 MXW and MXW-F Berea 250 cores.

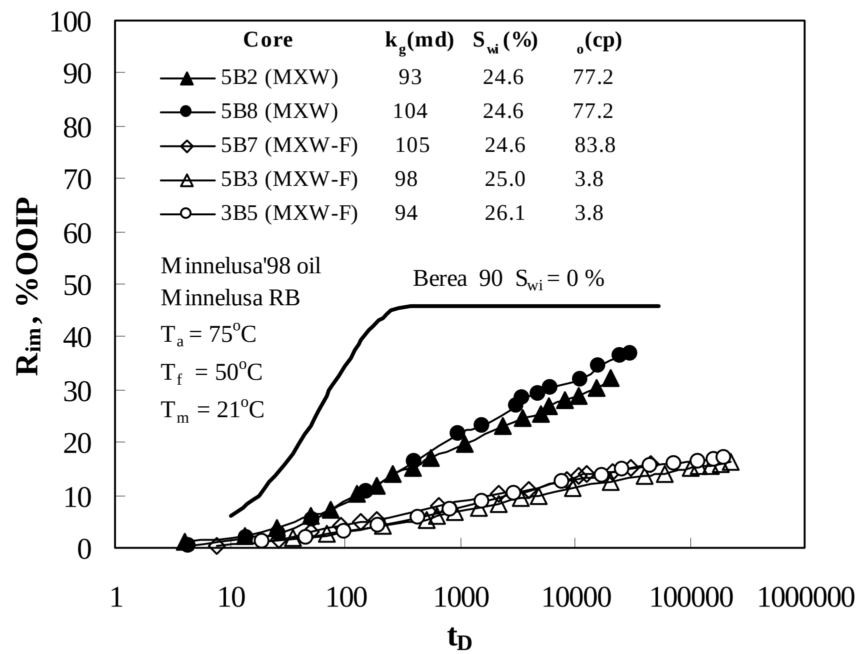

Figure 6. Comparison of imbibition between Minnelusa'98 MXW and MXW-F Berea 90 cores.

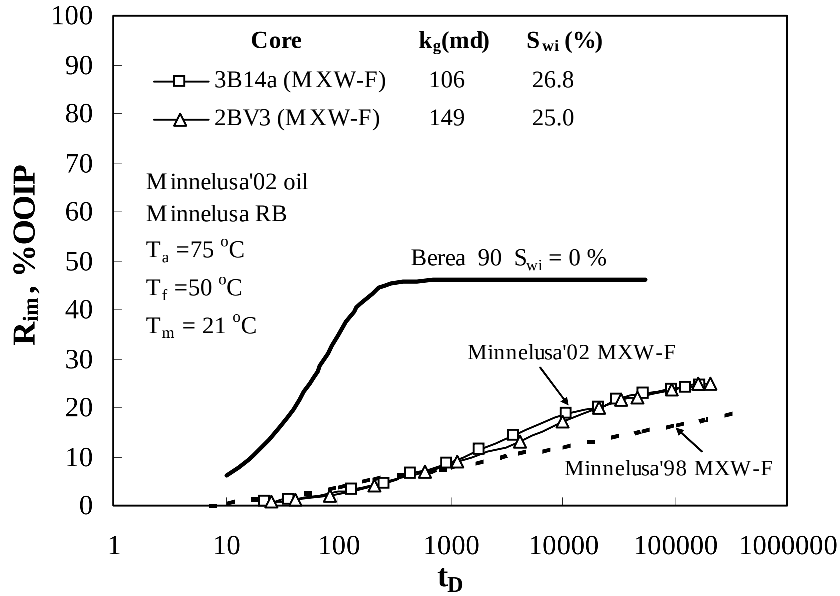

Figure 7. Comparison between Minnelusa'98 and Minnelusa'02 MXW-F Berea 90 cores.

3.4 Stability of MXW-F

The stability of the organic film deposited on the on the rock surface was tested for consecutive cycles of imbibition and drainage (Tong et al. 2002b and c). The results are shown in Fig. 8

After the 1st cycle of imbibition, the brine in 5B7 was displaced by mineral oil at room temperature to re-establish initial water saturation. The displacement rate ranged from 0.1 to 6.0 ml/min (about 0.36 to 22.5 PV/hr) based on the viscosity of the mineral oil and the desired S_{wi}. Five cycles of imbibition tests were performed on this core. The imbibition behavior shows good reproducibility indicating that the film on the rock surface is stable.

The stability of the MXW-F was also tested on another MXW-F core (3B5). Oil recovery versus dimensionless time is presented in Fig. 9. The close agreement in the first three imbibition curves indicated that that wetting conditions for the core did not change significantly during this series of tests.

3.5 Effect of SBM components on MXW-F cores

3.5.1 SBM base oil

After the 5th imbibition into 5B7 and 2nd imbibition into 3B5, S_{wi} was re-established by displacement with viscous mineral oil, which was in turn displaced by oil of selected viscosity (83.8 cp for 5B7 and 3.8 cp for 3B5). Then, the cores were aged for 10 days. The results shown in Figs. 8 and 9 indicate that the re-aging at S_{wi} had minor effect on wettability.

After the 6th imbibition, S_{wi} was re-stored for the 5B7 core by flow of the heavy mineral oil. The heavy oil was displaced with 5 PV of LVT 200 oil. Fig.8 shows that the scaled imbibition behavior of 5B7 treated with LVT 200 oil (viscosity of 2.9 cp) is close to those obtained for the previous six consecutive imbibition measurements made with reference mineral oils.

Another SBM base oil designated as Petrofree®SF was also tested. Fig.9 indicates that this SBM base oil also has no significant effect on the imbibition behavior of the Minnelusa MXW-F core.

3.5.2 SBM emulsifiers

After the 7th imbibition, S_{wi} was restored by flow of heavy mineral oil which was then replaced by injection of 5 PV of Soltrol 220 containing 0.015 vol % of LE SUPERMUL, an emulsifier used in synthetic oil-based mud. The subsequent imbibition test run on this core shows that the early stage imbibition rate was obviously suppressed because of exposure of the core to the emulsifier.

A second test was run for SBM emulsifier, EZ MUL®NT. After the 4th imbibition cycle, S_{wi} of 3B5 was restored again and then the viscous mineral oil was replaced with 5 PV of Soltrol 220 containing 0.0015 vol % of EZ MUL®NT. The curve with respect to the fifth cycle (see Fig.9) shows significant suppression of spontaneous imbibition.

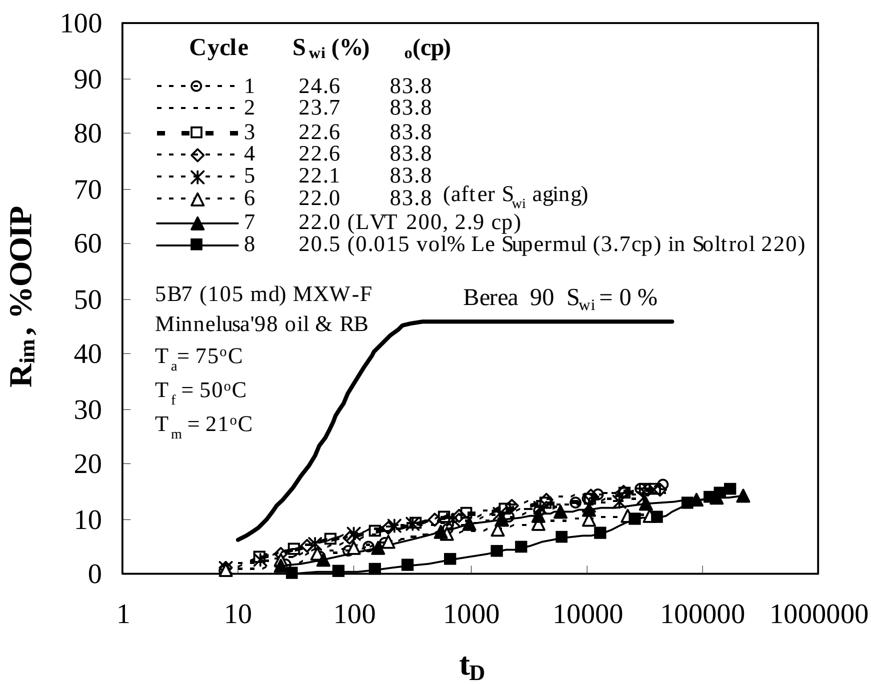

Figure 8. The effect of base oil and addition of emulsifier (LE SUPERMUL) on imbibition for Minnelusa'98 MXW-F Berea 90 core.

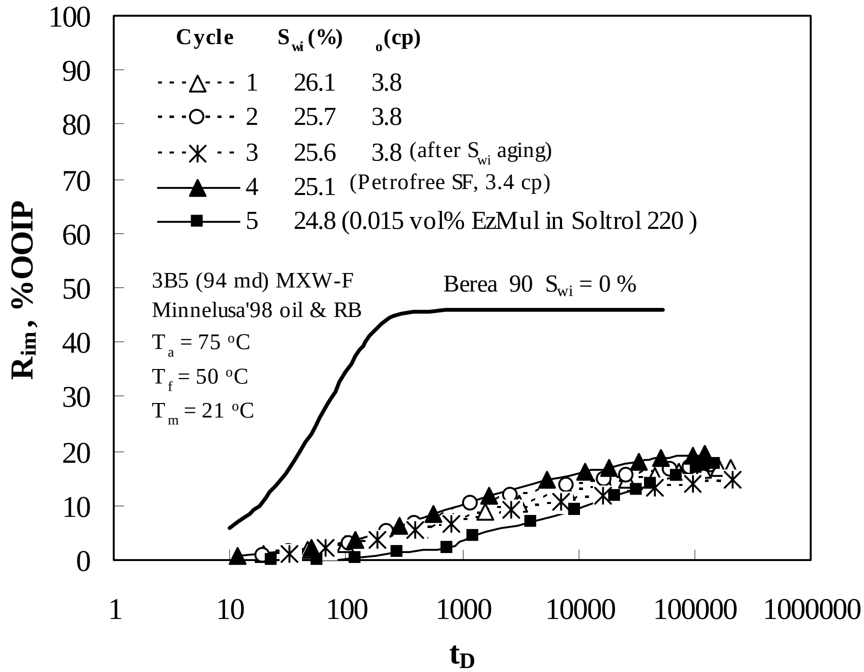

Figure 9. The effect of base oil and addition of emulsifier (EZ MUL®NT) on the imbibition of Minnelusa'98 MXW-F Berea 90 core.

4. Summary

1. A selection of crude oils rocks and base oils and additives for SBMs have been assembled. Basic characterization of rocks and oils are being obtained.

2. Baseline data for VSWW imbibition have been measured for a range of conditions.

3. Mixed wettability cores have been prepared by adsorption from two distinctly different types of crude oil. Results could be reproduced and the wetting states were stable with respect to repeated imbibition cycles.

4. Base oils for SBM muds had no significant effect on the wettability of MXW-F cores.

5. SBM emulsifiers caused a significant reduction in imbibition rate for MXW-F cores.

5. Nomenclature

I_w wettability index to water;

I_o wettability to oil;

I_{Amott} Amott wettability index;

k air permeability, md;

L_c characteristic length;

t imbibition time, min;

t_D dimensionless time;

R calculated oil recovery, fraction;

R_o final oil recovery, fraction;

T_a aging temperature, ^oC;

T_f flooding temperature, ^oC;

T_m measurement temperature, ^oC;

V_{oi} oil production by spontaneous imbibition, ml;

V_{of} oil production by forced imbibition, ml;

V_{wi} water production by spontaneous imbibition, ml;

V_{wf} water production by forced imbibition, ml;

α coefficient;

ϕ porosity, fraction;

μ_o oil viscosity, cp;

μ_w water viscosity, cp;

σ interfacial tension between oil and brine, mN/m;

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