

WETTABILITY AND RELATIVE PERMEABILITY OF LOWER CRETACEOUS CARBONATE ROCK RESERVOIR, SAUDI ARABIA

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ABSTRACT

Results and discussions in this paper relate to a Lower Cretaceous carbonate reservoir located in southeastern Saudi Arabia. It is a heterogeneous carbonate formation with various facies due to diagenetic alteration of the original rock fabric. The reservoir is large and prolific with mixed-wet characteristics. Because of the economic importance and variety of oil-recovery mechanisms operative or possible in the reservoir, the multi-phase recovery behavior has been extensively studied. Also, various wettability tests were carried out using Amott and USBM methods.

This paper describes the variation in wettability and relative permeability of Lower Cretaceous carbonate reservoir and the multi-phase simulations of the experimental results. It shows that measurements are consistent with recent theories of the relationship between water saturation, relative permeability, and wettability as described by Jadhunadan and Morrow, 1991. However, the results indicate that the wettability of the reservoir changes from water-wet low on structure near the oil/water contact to mixed or neutral wet behavior higher on structure. Oil-wetting character increases towards the top of oil column and is correlated to decreasing water saturation. The results revealed that changes in wettability are accompanied by changes in waterflood efficiency and facies of deposition.

INTRODUCTION

Carbonate reservoirs are characterized by extremely heterogeneous porosity and permeability. These heterogeneities are caused by the wide spectrum of environments in which carbonates are deposited and subsequent diagenetic alteration of the original rock fabric.

Lower Cretaceous formation (Shu'aiba) is one of the most productive carbonate reservoirs in the Middle East. It is a persistent shelf limestone that extends in the subsurface over much of the Arabian Gulf from Iraq to Oman and outcrops on the Musandam Peninsula, northern Oman.² In Saudi Arabia; the Shu'aiba formation (Aptian) is the uppermost member of Thamama Group. It overlies the Biyadh formation and in turn is overlain by the Albian Khafji sandstone, the lowest member of Wasia Group.

Shaybah field has been developed to produce oil from the Shu'aiba reservoir and is located in the Eastern Rub'Al-Khali ("The "Empty Quarter") of Saudi Arabia. The formation is heterogeneous carbonate rock, which consists of reef, lagoonal, and deep-water carbonate accumulations. The oil column is overlain by a large gas cap and

underlain by an active aquifer. The temperature range of the formation is 180-195 °F. The produced crude has an °API stock gravity of 41 and a dynamic viscosity of 2.83 mPa.s at 70 °F. Wells and production facilities are situated on the interdune sabkhas. The associated gas, representing an average gas oil ratio (GOR) of 750 SCF/STB, is separated, compressed to 3500 psig, and re-injected into the gas cap.

The depositional setting of the Lower Cretaceous reservoir in Shaybah field is grouped into four general facies zones. These are as follows:

- a) Fore barrier and slope facies association typically has 10 to 30 % in situ rudist accumulation and transitional to basin sequences.
- b) Rudist barrier facies association typically has 60 to 80 % rudist accumulations.
- c) Back barrier facies association typically has 20 to 40 % rudist accumulations and transitional to lagoonal sequences.
- d) Lagoonal facies generally have no rudist accumulations. The agrioplura characteristics are observed in the top zone while Miliolid characteristics are observed in the lower zone.

Knowledge of the preferential wettability of reservoir rock is of utmost importance to petroleum engineers and geologists. For example, a waterflood in a strongly oil-wet rock is much less efficient than one in a water-wet rock.³ In the past, many engineers assumed that most reservoir rocks are water-wet. The reasons for this conviction are the work of Leverett (1941)⁴ and test methodology of determination of wettability after thoroughly cleaning cores that were likely to have been contaminated and exposed to air.

The paper published by Treiber et.al⁵ was the major breakthrough in showing that the large numbers of carbonate reservoirs are oil-wet. Consequently, various studies showed that the wettability of carbonate rocks is oil-wet, neutral or mixed.⁶⁻⁷ This paper provides a case study in which wettability of preserved core samples from Lower Cretaceous Saudi carbonate reservoir have been measured to characterize wettability and its effect on waterflood behavior.

Relative permeability is a rock characteristic that describes quantitatively the simultaneously flow of two or more immiscible fluids through porous media. This property is important for predicting fluid movement in a reservoir during various recovery processes. Relative permeabilities can be obtained from the following sources (a) reservoir production data⁸ (b) published data on general rock types⁹ (c) laboratory displacement tests using representative reservoir rocks and fluids.¹⁰ The most reliable source is laboratory measurements of relative permeability. The two methods used for laboratory measurement of relative permeability are unsteady state and steady state. It is postulated that the unsteady state method simulates a waterflood process more closely than the steady state in obtaining relative permeabilities.

The current study is a cooperative project to fully characterize the Shu'aiba reservoir. Because of the geologic complexity of the Shu'aiba formation and the variety of oil-recovery mechanisms, extensive wettability and waterflooding studies have been conducted to assist reservoir simulation and reservoir management departments to

develop the proper production strategy for Shaybah field. Wettability evaluation was performed using USBM and modified Amott techniques. Unsteady state relative permeability measurement was performed on lithofacies in Shu'aiba reservoir using composite cores arrangement.¹¹

Reservoir Mineralogy

XRD and XRF analyses revealed that the most predominant mineral in the Lower Cretaceous carbonate rocks is calcite (90-100 weight %). The other minerals are dolomite (0-8 weight %), and trace amounts (< 0.5 weight %) of quartz, pyrite, ankerite, gypsum, and siderite. The results also indicated the presence of very minor amounts of barite, halite, and sylvite. The source of these three minerals is drilling fluid contaminants.

PLUG SELECTION AND TEST FLUIDS

Core material from Lower Cretaceous carbonate reservoir was cut with a KCl brine and packed under de-aerated KCl brine in plastic tubes. Core plugs of approximately 3 inches in length and 1.5 inches in diameter were drilled from the whole core at 0.5-foot intervals with brine identical to the preserving brine. The drilling direction is perpendicular to the axis of the whole core. After trimming, the plugs were wrapped with silver paper and then placed in sealed container completely submerged in evacuated KCL brine.

Visual, brine permeability at remaining oil saturation, and CT scans were performed as screening tests to assist in sample selection. The screening tests were combined with a review of conventional core data and geological description of the core material to ensure that anomalous samples were not tested. Cores that were fractured, broken, or displayed brine permeability less than 1 millidarcy (mD) were excluded from further testing.

Wellhead oil from Lower Cretaceous carbonate reservoir was used as the oleic phase in the wettability experiments and recombined live oil with dynamic viscosity of 0.41 mPa.s at reservoir conditions (temperature=190 °F and pressure=2500 psig) was used in relative permeability tests. The aqueous phase was synthetic brine (similar to reservoir brine). **Table 1** presents the composition of the synthetic formation brine used to saturate the core plugs and carry out the wettability and relative permeability tests. The viscosity of this brine is 0.42 mPa.s at reservoir condition. In addition to sodium and chloride ions as the main components of the brine, divalent calcium and magnesium are also abundant.

EXPERIMENTAL PROCEDURE

Wettability Measurements

Amott Method

Wettabilities of preserved core plugs were measured by modified Amott method.¹² The Amott method combines spontaneous imbibition and dynamic displacement that performed under ambient conditions with simulated formation brine and stock tank oil.

For spontaneous processes, the sample is submerged in the fluid to be imbibed and the

displaced volume of nonimbibed fluid is measured. The dynamic displacement involves flowing the imbibing fluid through the sample and measuring the displaced volume of the other fluid. The displacement volumes (both spontaneous and total) are measured for both oil and water. The ratio of the spontaneously displaced volume to the total displaced volume is calculated for both the oil and water phases. The Amott-Harvey wettability index is the displacement-by-water ratio minus the displacement-by-oil ratio.

If a sample spontaneously imbibes only brine, it is considered water wet. Similarly, if it imbibes only oil, it is considered oil wet. If the sample imbibes neither, it is described as neutrally wet.

Wettability Measurements: USBM Method

The United States Bureau of Mines (USBM) method was used to measure wettability. USBM wettability index is obtained from the drainage/imbibition hysteresis loop given by centrifuge capillary pressure curves.¹³ The areas under the curves represent the thermodynamic work required for the respective fluids to displace each other. The logarithm of the ratio of the area of oil-displacing-brine (A1) to brine-displacing-oil (A2) is used to identify the USBM wettability index.

For purpose of discussion, the wettability index range from +1 to -1 was subdivided and classified as follows: neutral or mixed (-0.1 to 0.1), slightly water-wet (+0.1 to +0.3), water-wet (+0.3 to +1), slightly oil-wet (-0.1 to -0.3), and oil-wet (-0.3 to -1).

Relative Permeability Measurements

The procedure for relative permeability measurements included the use of composite core¹¹ assembled from core material cut with KCl brine and preserved at the well site. The unsteady-state relative permeability tests were conducted at simulated reservoir conditions of 190 °F, 2500 psig pore pressure, and 5000 psig confining pressure using recombined (live) and synthetic brine similar to reservoir brine.

In preparation for testing, a brine-saturated composite core was assembled, placed into a rubber sleeve, and loaded into horizontal coreholder. Dead oil was flushed through the composite under backpressure to displace gas and ensure complete fluid saturation. Reservoir conditions of 190 °F and 5000 psig confining pressure were established.

Recombined live oil was injected to displace the dead oil. After a period of aging, the core was stabilized by pumping several pore volumes of live oil until a constant pressure drop was obtained. After pressure stabilization, baseline oil permeability was determined. Methane-saturated brine was injected to simulate a waterflood processes. A constant flow rate of 2 cm³/min was maintained. This rate was chosen to minimize capillary end effects. These effects are minimal when the scaling factor ($L\mu V$) is greater than 2 based on scaling criteria proposed by Rapoport and Leas.¹⁴ L is the core length (cm), μ is displacing phase viscosity (centipoise) and $V = q/A$ is flow rate per unit cross-sectional area of the composite core (cm/min). Both oil and water volumes were measured at reservoir condition by an acoustically monitored separator. Relative permeabilities were calculated using JBM method.¹⁵

At the end of waterflooding, the core composite was allowed to cool. All produced fluids were collected. The core holder was disassembled. The cores were weighed and placed in the Dean Stark extraction apparatus where water and oil were extracted using toluene. The extracted samples were then dried in a vacuum oven at 150 °F for two days. Air permeability and porosity for each plug was measured at high confining stress (2500 psig).

RESULTS AND DISCUSSION

Wettability

Wettability is a surface phenomenon. It is defined as the tendency of one fluid to spread on or adhere to a rock surface in the presence of another immiscible fluid. It has a significant effect on oil recovery produced by waterflood or by water-drive mechanisms. Therefore, it is necessary to determine preferential wettability of the reservoir, whether this be to water, or oil or somewhere between the two extremes i.e. intermediate.

In this study wettability indexes were obtained from USBM and Amott methods. Figure 1 shows an example of capillary pressure curves used to compute the USBM wettability indices of cores. The abscissa is the average water saturation and the ordinate of each plot is the capillary pressure. The areas under the curves are designated as A1 and A2. The results of wettability tests showed full range of wettability indices that ranged from -0.71 to 0.82. Figure 2 shows the plot of wettability indices as a function of core depth. The scale of the plot is from -1 (strongly oil wet) to +1 (strongly water wet). The figure indicates variation of wettability indices with relative level from water-oil contact and gas-oil contact. Core material recovered from the interval located above the gas-oil contact revealed oil-wet character and the plugs from oil zone showed oil-wet to intermediate wettability character. On the other hand, the samples recovered from zone located below the water-oil contact are water-wet. Hence, data showed strongly oil-wet upstructure to intermediate wettability in the mid-structure region. Water-wet behavior is shown near the oil-water contact with a tendency for increasing water-wet characteristics with depth.

The wettability index to water (WI) for plugs tested with Amott method will be used to explain the relationships with rock quality and structural position. Figure 3 shows that

wettability index to water decreases as the sample height above the water-oil contact increases. Samples close to water-oil contact are water-wet, whereas intermediate wettability is obtained high above the water-oil contact. In addition, rock quality has effect on wettability index. Figure 4 shows that the variation of the wettability index to water with change of permeability of core plugs. There is a general trend of increase in water wetness with decrease in permeability. Hence, the results revealed that wettability index to water depends on both rock permeability and structural position of the samples. A correlation between Amott wettability index (AWI) and initial water saturation (S_{wi}) is obtained from Figure 5. The figure shows a strong correlation between S_{wi} and AWI with more water-wet behavior at higher initial water saturation. The trends in these data are essentially the same as those observed by Jadhunadan and Morrow¹ in Berea sandstone and confirm the idea of dependence of wettability on S_{wi} for mixed-wet systems. The cross-plotting of Amott indices to water and Amott indices to oil in a

ternary plot was proposed by Mitchell et.al.¹⁶ as a way of quantifying wettability characterization. This approach was adopted in this work and is illustrated in Figure 6. The data shows neutral to intermediate and water wet characteristics of core materials.

The results indicate that wettability of Lower Cretaceous carbonate reservoir was found to have a heterogeneous nature (mixed wettability). The heterogeneities may be related to variation of facies and environment of deposition, which result in variation of pore size distribution.¹⁷ Our results confirm the conclusions of Marzouk¹⁸ and Cuiec⁶ about wettability variation of carbonate reservoirs versus height. Similar observations and trend were obtained from sandstone reservoir characterized by mixed wettability as reported by Jerauld¹⁹ and Morrow.²⁰

Relative Permeability

Seven relative permeability curves were measured on preserved reservoir samples taken from a range of locations ranging from up-structure, mid-structure, and down structure. All measurements were taken on composites of three or four core plugs. Composites are used because they are believed to be least impacted by core-scale heterogeneities. They provide more precise data because the pore volume and pressure drop are both larger, and are least impacted by capillary and inlet end effects. Table 2 summarizes the recovery performance of all seven composite cores that were used in the relative permeability experiments.

Results in Table 2 showed that oil recovery ranged from about 26 to 62 % at breakthrough and reached an ultimate recovery in the range of about 46 to 76 % of pore volume. The residual oil saturation (S_{or}) varied between 6.6 and 31 % of pore volume at the end of waterflooding. The irreducible water saturation (S_{wir}) ranged from about 5.7 to 37 % of pore volume.

In an attempt to investigate the trend between relative permeability with depth, the tested composites were selected from different depth intervals up-structure to down structure. Composites 1, 2, and 3 were taken from the up-structure zone. A semi-log plot of relative permeability curves versus water saturation ratio for these composites is shown in Figure 7. The plot reflects oil-wet behavior of these composites, based on Craig's rule of thumb.²¹ Relative permeability to water at the end of waterflooding (K_{rw}) ranged from 49 to 100 %. The relative permeability curves for the two composites recovered from mid-structure zone (composites 4 and 5) are shown in Figure 8. Their behavior revealed mixed-wettability character. K_{rw} at S_{or} for composites 4 and 5 are 31 and 57 %, respectively. The behavior of the last two composites from down-structure is water-wet character. Figure 9 indicates relative permeability curves for composites 6 and 7. K_{rw} at S_{or} is 29 % for both composites 6 and 7.

From wettability and relative permeability results described above, it can be stated that trends in relative permeability and wettability for Lower Cretaceous carbonate reservoir are consistent. Core plugs taken higher in the structure appear to be oil-wet and plugs taken down-structure were water-wet. Hence, the trends in relative permeability with depth were similar to those generally ascribed to the variation of relative permeability with wettability.²²

CONCLUSIONS

1. Wettability characterization of Lower Cretaceous heterogeneous carbonate reservoir illustrated that wettability heterogeneities are very broad.
2. Amott wettability results and USBM wettability indices showed large variation of wettability with depth. Data revealed strongly oil-wet upstructure to mixed or intermediate wettability in the mid-structure region. Water-wet behavior is shown near the oil-water contact with a tendency for increasing water-wet characteristics with depth.
3. Structural position could be a factor that controls vertical variation of wettability.
4. Unsteady-state relative permeability results indicated considerable oil recoveries with substantial recovery occurring beyond breakthrough. The residual oil saturation (Sor) varied between 6.6 and 31 % of pore volume at the end of waterflooding. The irreducible water saturation (Swir) ranged from about 5.7 to 37 % of pore volume.
5. Trends in relative permeability and wettability for Lower Cretaceous carbonate reservoir are in agreement. Core plugs taken higher on structure appear to be oil-wet and/or mixed-in wettability and plugs taken down-structure had water-wet character.

ACKNOWLEDGEMENTS

Appreciation is given to the Saudi Arabian Oil Company (Saudi Aramco) for granting permission to present and publish this paper. The authors wish to thank the management of Research and Development Center. Special thanks to Petrophysics Unit personnel for their efforts in experimental work.

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TABLE 1- Chemical Analysis of Formation Brine.

Variable	Value
Sodium, mg/L	49,880
Calcium, mg/L	16,480
Magnesium, mg/L	2,146
Sulfate, mg/L	191
Chloride, mg/L	112,180
Total dissolved solids (TDS), mg/L	180,877
Sp.Gr. @ 60 °F	1.1295
PH	6.2

TABLE 2 – Summary of Waterflood Performance Data for Composite Cores.

Composite No.	Location	Breakthrough Oil recovery (% PV)	Final Oil recovery (% PV)	Swir (% PV)	Sor (% PV)	Ko at Swir (mD)
1	Up-structure	26	46.5	37.1	16.4	14.8
2	Up-structure	67	74	6.9	19.1	1.9
3	Up-structure	64	76.3	17.1	6.6	3.5
4	Mid-Structure	63	69.8	14.6	15.6	2.6
5	Mid-Structure	44	57.3	32.2	10.5	10.4
6	Down-Structure	59	63	5.7	31.3	0.5
7	Down-Structure	38	52.2	34.2	13.6	7.1

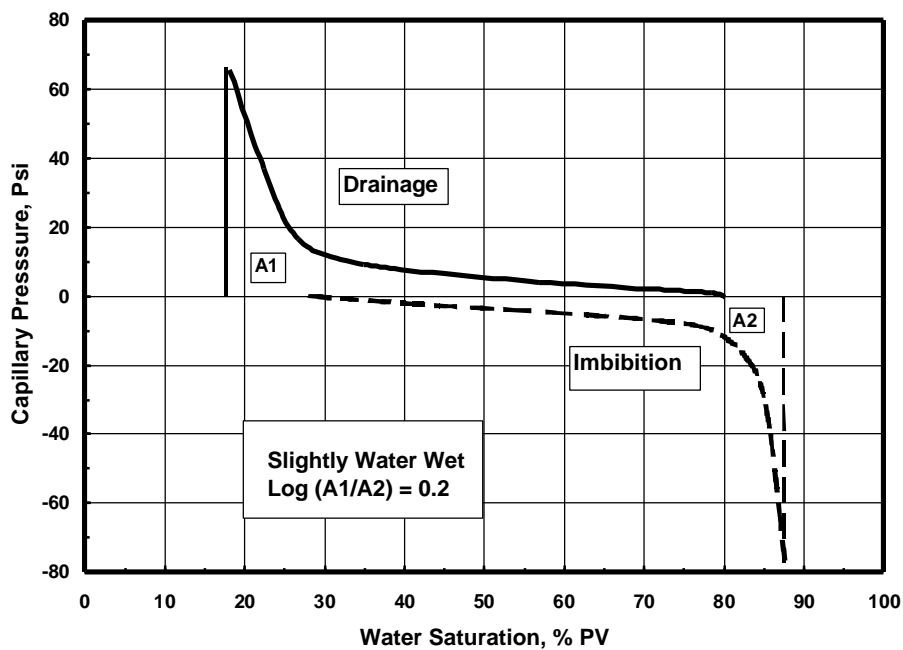


Figure 1: Example of Centrifuge Capillary Pressure Curves Used to Compute Wettability Indices of Core Plugs.

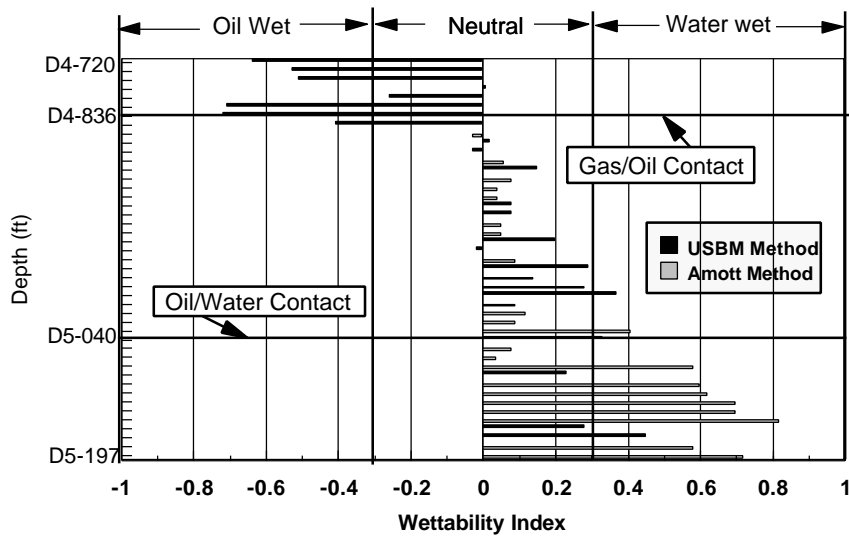


Figure 2: Wettability Distribution Vs. Depth for Lower Cretaceous Carbonate Reservoir.

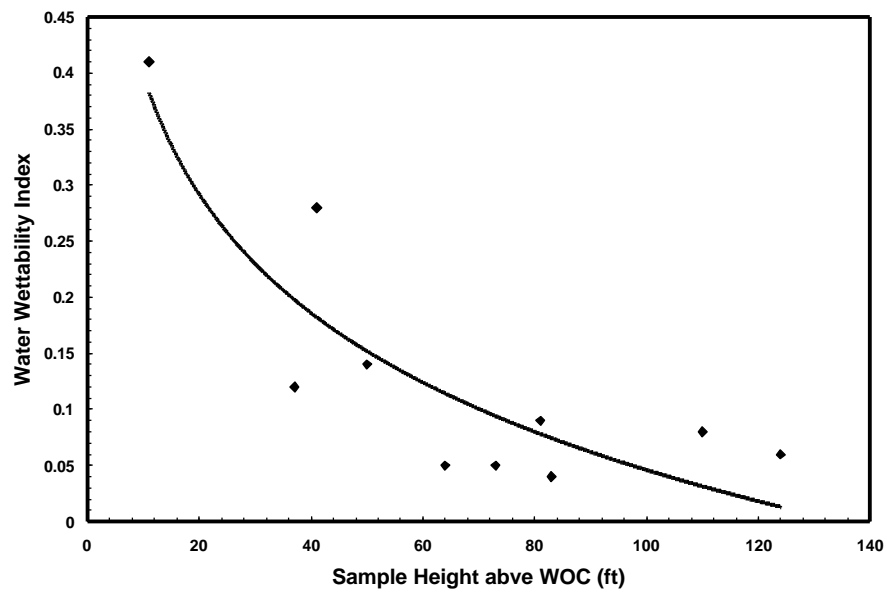


Figure 3: Relationship between Wettability Index to Water (WI) and Structural Position.

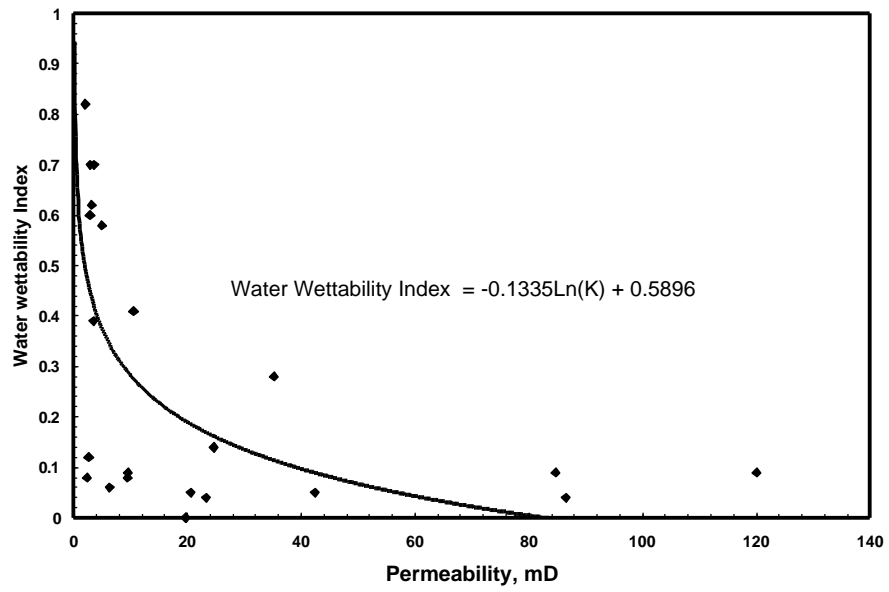


Figure 4: Relationship between Wettability Index to water (WI) and core permeability.

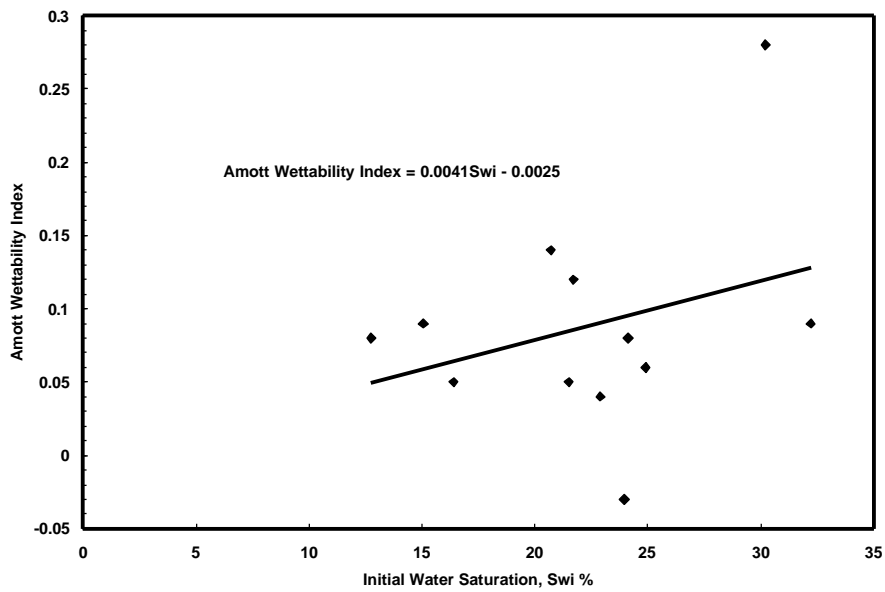


Figure 5: Relationship between Amott Wettability Index (AWI) and Initial Water Saturation.

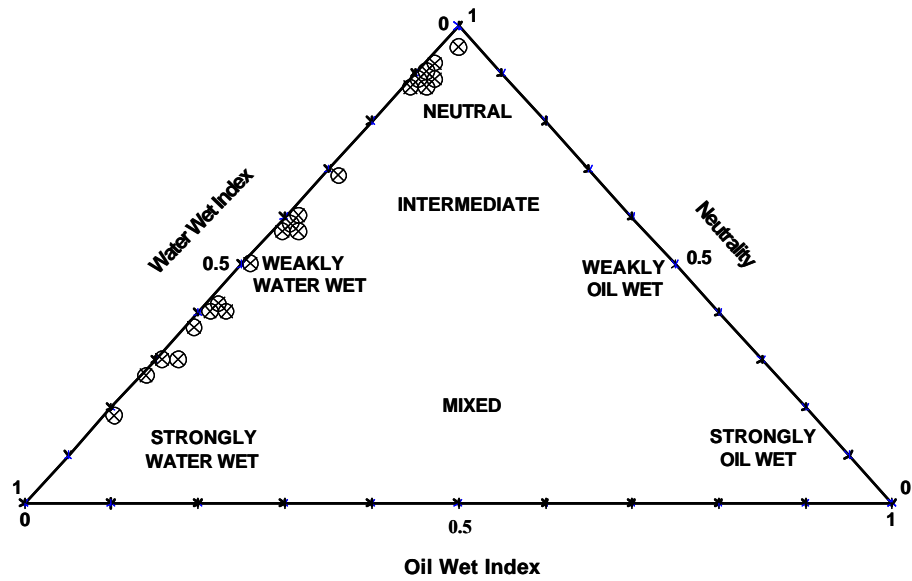


Figure 6: Ternary Plot Diagram of wettability Indices for Lower Cretaceous Carbonate Reservoir.

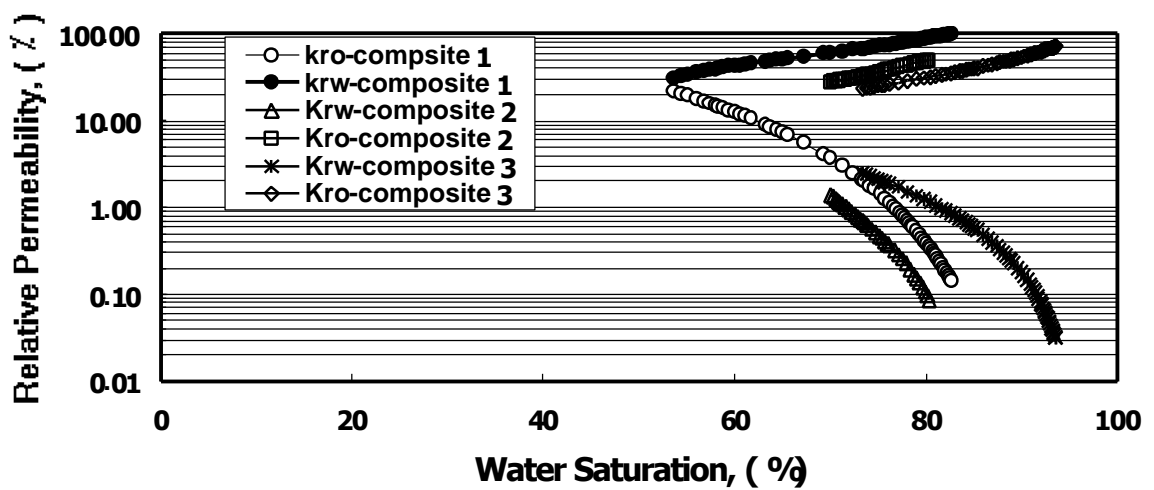


Figure 7: Relative Permeability curves of composites from Up-structure zone.

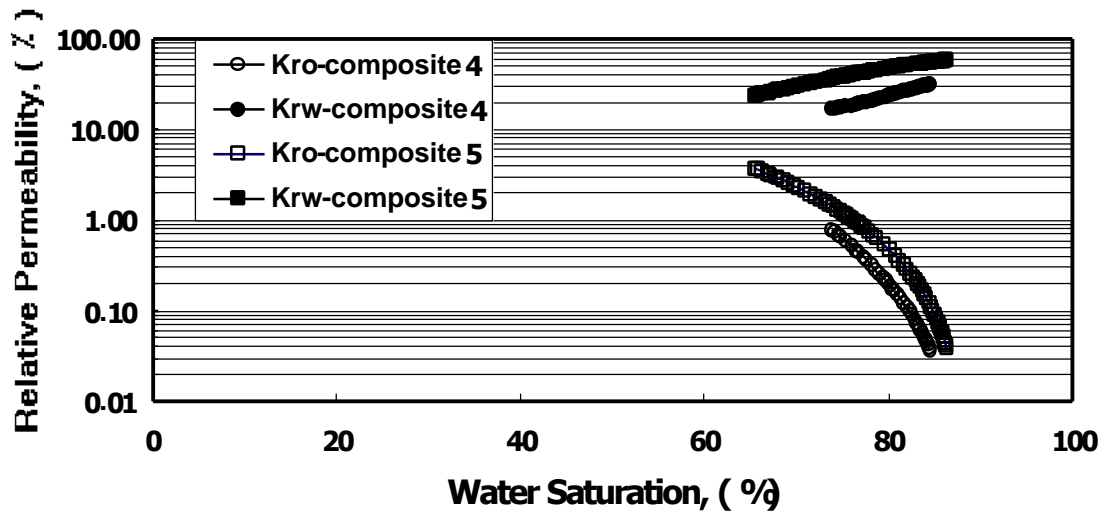


Figure 8: Relative Permeability curves of composites from Mid-structure zone.

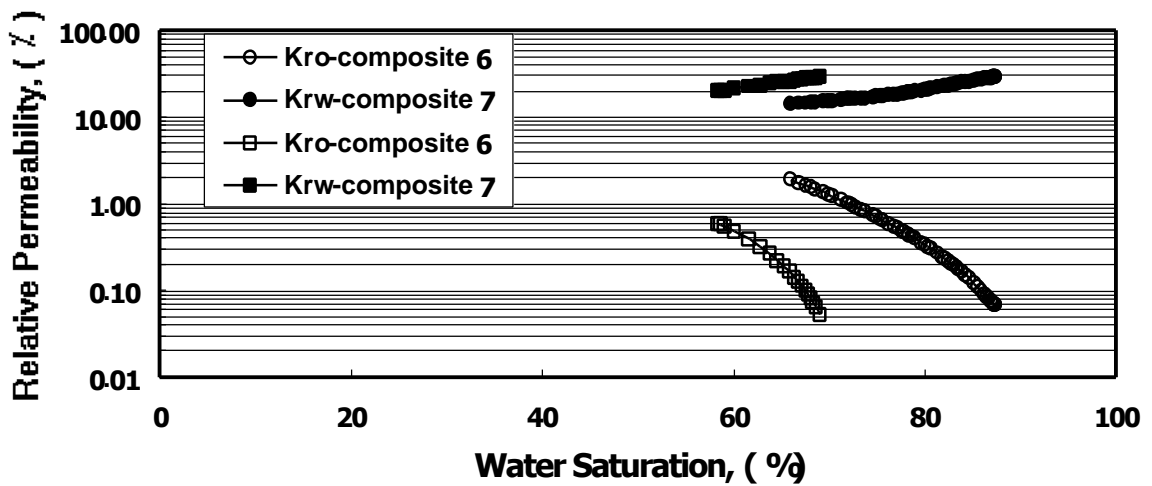


Figure 9: Relative Permeability curves of composites from Down-structure zone.