Role of Rock Wettability on Relative Permeability and Capillary Pressure Behavior

by

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16575

Dissertation submitted for partial fulfilment of

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January 2015

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CERTIFICATION OF APPROVAL

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(PETROLEUM)

Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein not been undertaken or done by unspecified sources or persons.

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(GADIS VIKHA NATARI)

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ABSTRACT

Rock wettability is one of the factors that affecting flow mechanism of reservoir, such as relative permeability and capillary pressure. These properties are important to determine the effective production and choose the suitable recovery methods of the reservoir. This paper will discuss the studies done on wettability of carbonate rocks, in order to differentiate and analyze the flow properties hysteresis when the wetting phase of the rocks are different.

Analysis on capillary pressure for different wetting phase shows different hysteresis on the curve and wettability index, which ranged between -0.85 to +0.35. Observation of Lambda from the graphs, also show the irreducible water saturation values and can identified the type of the sand reservoir and permeability. Moreover for relative permeability curve, it shows also different trend for different wetting phase, although the hysteresis did not satisfy all Craig's rule of thumbs. The difference of hysteresis in different cores samples show that for improvement of production, water-flooding is better to be used in water wet condition and in order to have better accuracy, measurement with solely method is not sufficient.

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CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

In oil and gas industry, especially in reservoir engineering area, wettability has been tremendous interest as it is one of important factor to predict several reservoir parameters, namely relative permeability, capillary pressure, water-flooding, and oil recovery. According to Treiber et. al. (1972), wettability is affected by several significant factors, including water saturation interpretation, laboratory experiment for cores samples, and recovery enhancement. Firstly, wettability is affected by water saturation in order to determine water saturation in reservoir, typically log response of Archie’s method is used. The value of saturation exponent relates to wettability. Secondly, during displacement of core test analysis, the result of significant types of wettability is able to predict the reservoir performance. Lastly, the original wettability of reservoir is able to predict the method for improving the recovery process.

Hydrocarbon is usually found in sandstones and/or carbonates formation. It is identified that 50% of proven petroleum reserves are from carbonate formations, which have low recovery. The causes of low recovery factor are due to several factors, such as wettability and reservoir fractured nature. Most of carbonates rocks are recognized as oil wet instead of water wet (Chilingar &Yen, 1983). On the contrary, as discussed by Falode and Manuel (2014), carbonates, known as materials that have most common aquifer, is categorized as water wet. The differences in the statement may occur due to numerous factors. One of the factors is some alteration that may occur when the core sample are brought into laboratory, as in-situ measurement could not be done for wettability test.

1.2 PROBLEM STATEMENT

Carbonates formation are known as one of the sources where the hydrocarbon is usually found. However, the determination of fluid distribution on the formation, known as wettability, become one of the concern which this project will be focusing on wettability of carbonates formation. As it is known that the wettability is one of the factors affecting reservoir parameters, such as relative permeability and capillary pressure, the difference wettability state of the rocks will affect the hysteresis of capillary pressure and relative permeability curves.

The states of the cores also put under consideration as in-situ measurement is not able for wettability, instead laboratory experiment is needed. Moreover, by knowing the hysteresis of the reservoir properties, the recovery method for improvement of production can be estimated for the future.

1.3 OBJECTIVE AND SCOPE OF STUDY

The objective of this project is as follow:

- To analyze the effect of different wetting phase toward relative permeability and capillary pressure.

The scope of this study includes:

- Conducting research on theories of wettability done by previous researchers.
- Conducting procedure to achieve the objective which is to analyze the hysteresis of relative permeability and capillary pressure on different wetting phase.

CHAPTER 2

LITERATURE REVIEW

The investigation of this project is focusing on characteristics of rock in terms of wettability along with the flow properties. Hence, the literatures on these factors will be discussed in-depth in this chapter.

2.1 CARBONATE ROCKS

Carbonate rocks are classified as the most abundant non-terrigeneous sedimentary rocks which composed by mineral known as carbonate. There are two most common types of these rocks, which are limestone and dolomite. Carbonates are also known as holding 60% of oil and 40% of gas as reservoir rocks (Schlumberger Market Analysis, 2007). However, due to its complexity, development of reservoir having carbonate rocks create several problems compared to development of sandstones.

2.2 WETTABILITY

Wettability is defined as ability of fluid to adhere on solid surface while other immiscible fluids present (Craig, 1971). Falode and Manuel also stated that wettability is known as one of the factor that essential to control the flow of oil and water in pore spaces. Although the rocks have the same categories, the wettability may varied due to several factors, including surface roughness, water and oil composition, rock mineralogy, temperature and pressure, and thickness of water film.

In the early years, many research had been done regarding the wettability of reservoir rocks which stated that wetting characteristics of the reservoir rocks were assumed to be uniform and strongly water wet (Morrow, 1990). However, when further investigation were done, it showed the contrary, which reservoir rocks were mostly not strongly water wet and tend to be heterogeneous.

In equilibrium system, the pores of the rock will be occupied by two phases, which are wetting phase and non-wetting phase (Zahoor et. al., 2009). Wetting phase tends to immerse in small pores and adhere on solid rock surface, while non-wetting phase will occupy the center of large pores and form tiny drop. It is also identified that the wetting phase tends to have lower permeability compared to non-wetting phase.

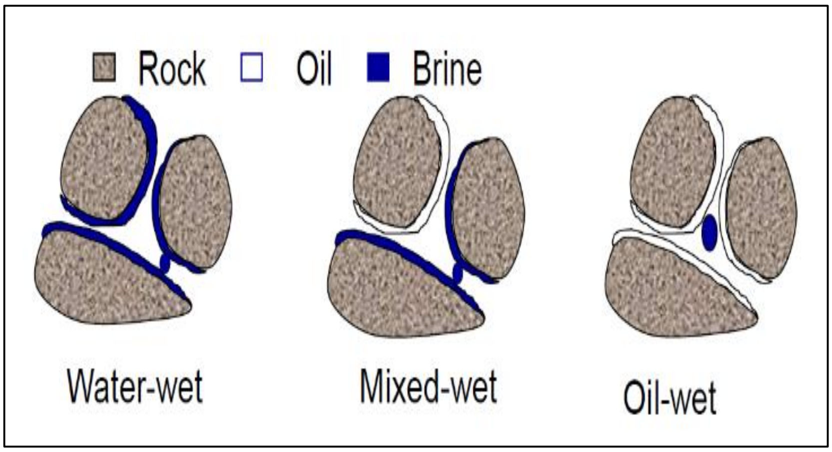

Figure 1: Adherence of wetting and non-wetting phase

One of the factor that can be determined by wettability is oil recovery. Oil recovery can be differentiate into three types, which are primary, secondary, and tertiary. The most commonly applied, relate it with wettability, is secondary recovery where water injection or water-flooding is applied. There are several researches done many years ago, which showed the contradictive argument about wettability phase that affect oil recovery. As the experiment done by Anderson (1987), it showed that the water wet condition will give more effective oil recovery compared to oil wet. However, Morrow (1987) argued that oil recovery would be maximum when the rock has intermediate wet due to oil that trapped and disconnected in the formation.

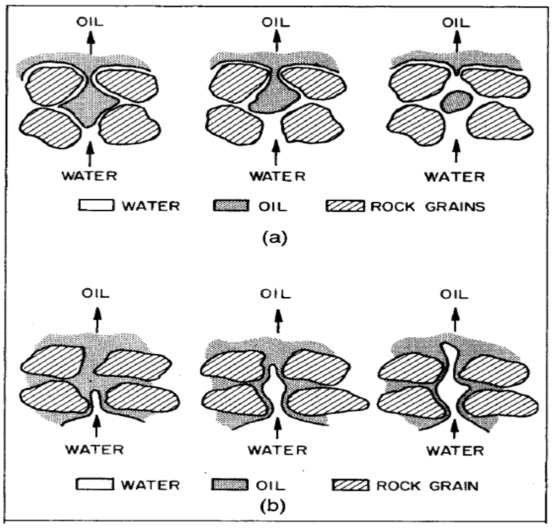

Figure 2: Water-flooding in water-wet and oil-wet

2.2.1 Wettability Classification

Wettability can be differentiated into two classifications, which are homogeneous and heterogeneous. These classifications are based on tendency of liquid to adhere on surface. For each classification of wettability, it also configures into several other types. In homogeneous wetting, the wettability can be differentiated into three types, including:

- Water Wet

  A condition where the water occupy small pores and rock surface, while the oil occupy center of large pores
- Oil Wet

  It is the contrary condition from strongly water wet. Oil wet occur as oil occupy small pores and rock surface, while water occupy larger pores.
- Intermediate Wet

  A condition when rock has no preference on wetting system for either oil or water.

In addition, for heterogeneous wetting, it can be differentiated into two types, namely:

- Fractional Wettability

  A condition when rock, originally, have a portion of strongly oil wet whereas the portion is mostly strongly water wet. It occurs as crude oil components, known as heavy oil, immerse in certain areas.
- Mixed Wettability

  Rock has a portion where the small pores are water wet meanwhile the large pores are oil wet and continuous.

2.2.2 Wettability Measurement

Numerous methods have been utilized in order to evaluate rock wettability, which are differentiate into two methods known as quantitative and qualitative method.

Qualitative methods are used when the degree of wettability will be determined based on shape of curves and behavior of particles in fluids. The most common methods to obtain the wettability of rock is as follow:

- Relative Permeability Curve

  It is suitable when large difference of wettability changes occur in cores. As discussed by Craig, the rules of thumbs need to be applied in order to determine the rock wettability, which can be seen as follow:

	Water-Wet	Oil-Wet
Interstitial water saturation	Usually greater than 20 to 25% PV.	Generally less than 15% PV. Frequently less than 10%.
Saturation at which oil and water relative permeabilities are equal.	Greater than 50% water saturation.	Less than 50% water saturation.
Relative permeability to water at the maximum water saturation (i.e., floodout); based on the effective oil permeability at reservoir interstitial water saturation.	Generally less than 30%.	Greater than 50% and approaching 100%.

Figure 3: Craig's rule of thumbs for determining wettability

In addition with the methods mentioned above, several other methods also used, such as:

- Imbibition Rates
- Dye Adsorption
- Glass Slide Method
- Microscope Examination
- Permeability / Saturation Relationship
- Capillary Pressure Curve
- Capillametric Method
- Reservoir Logs
- Nuclear Magnetic Resonance
- Displacement Capillary Pressure

On the other hand, several ways also recognize in order to determine wettability using quantitative methods, including:

- Contact Angle Measurement

  It is identified as the best method to evaluate wettability due to the usage of artificial core and pure fluids. Several ways can be utilized in this measurement. However, the most common used is sessile drop method which focusing on measuring the angle, termed as "θ", on smooth solid surface.

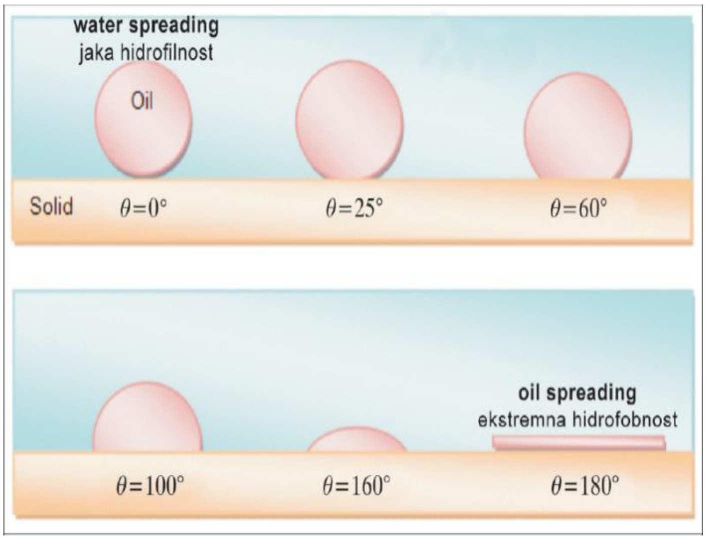

Figure 4: Contact angle at smooth solid surface

- Forced Displacement (Amott) and USBM

  Amott and USBM are known as method that measure the index of wettability, known as WI. Wettability index is ranged from -1 to +1 depending on wettability types. One of the advantages of this method is the wettability index measurement that able to provide the average wettability at the core, while the contact angle method only measures at localized scale.

$$I_{USBM} = \log(\frac{A_1}{A_2})$$

Table 1: Relationship of wettability, contact angle, amott, and USBM

		Water-Wet	Neutral	Oil-Wet
Contact Angle	Minimum	0	60-75	105-120
	Maximum	60-75	105-120	180
USBM	Wettability Index	W near +1	W near 0	W near -1
Amott	Displacement by Water Ratio	Positive	Zero	Zero
	Displacement by Oil Ratio	Zero	Zero	Positive
	Amott-Harvey Wettability Index	+1 to +0.3	+0.3 to -0.3	-0.3 to -1

- Measuring Streaming Potential

  Measuring streaming potential method, which has been experimented by Jackson and Vinogradov (2012), shows that core sample experiment can lead to aging the rock. Hence, the wettability is measured by using the core that saturated by oil sand brine.

2.3 NATIVE STATE CORE, CLEANED CORE, AND RESTORED CORE

There are three different state of cores usually use for core analysis which are native state, cleaned, and restored core. As it was mentioned previously that in-situ measurement is not possible, thus laboratory experiment is needed instead. One of the experiment done by Anderson, shows that native state core will provide best result for core analysis as no alteration is made to the cores. Another state of cores known is cleaned core, which the cores are altered to remove all the fluids and adsorbed organic material or solvents. However, this state of core is rarely used due to inaccuracy of measurement. The other most common state of cores is restored core, where the native state is restored by three methods. First, by cleaning the core and saturating with brine and crude oil. Lastly, the core is aged at reservoir temperature for about 1000 hours.

2.4 RELATIVE PERMEABILITY

Relative permeability is defined as ratio of effective permeability to its absolute permeability when more than one fluid presents. It is known as a critical parameter in order to evaluate performances of the reservoir. According to Anderson (1987), relative permeability is able to control the movement of two immiscible fluids in porous media. Relative permeability curves have several functions, including predict the production and recovery rate of the reservoirs for all stages of the recovery.

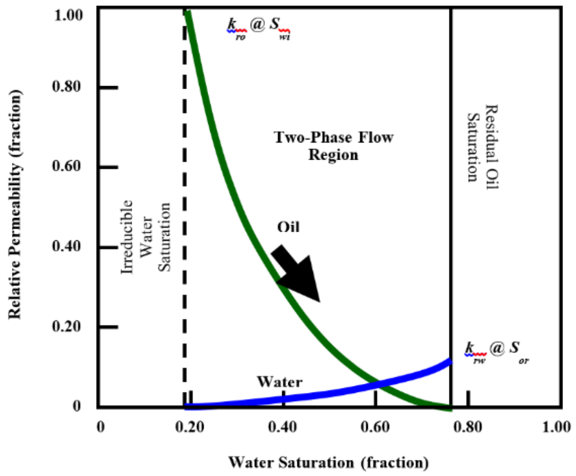

Figure 5: Relative permeability curve

Relative permeability is also essentially affected by numerous factors, as follow:

- Pore size distribution

  The pore structure, in term of shape and size, are different for each rock in the reservoir. These factors would affect the relative permeability as the fluid may flow through different interconnection. When non-wetting phase invades pore structure, it will enter the largest pore size that causing decrement in water permeability.

- Wettability

  Wettability is one of the factor that affecting flow properties, including the changes in relative permeability. These changes occur as water saturation changed. One of the example, from experimental done, was the differences of relative permeability for strongly oil wet and strongly water wet, that are shown in the figure below:

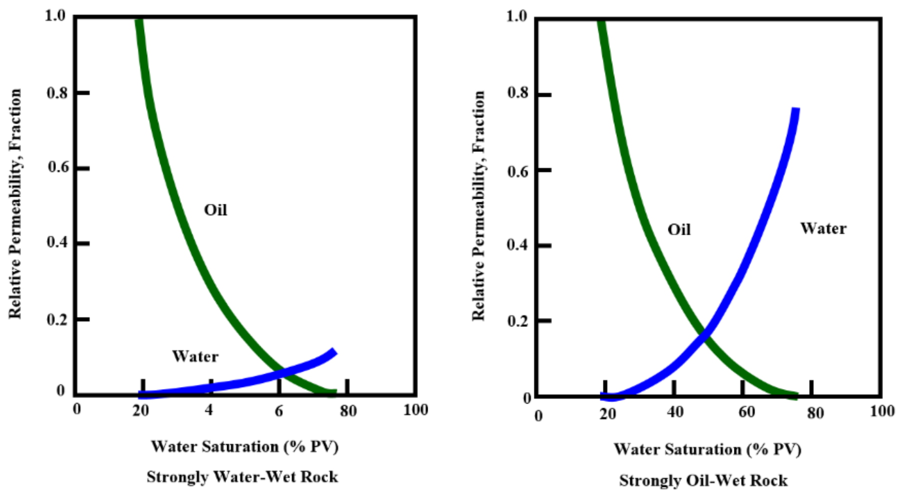

Figure 6: Typical relative permeability on water-wet and oil-wet

It is observed from the figure above that in oil-wet condition, the residual oil actually tends to be higher and water can flow freely. This hysteresis occurs when the rock has homogeneous wetting configuration. However difference hysteresis will occur when the rock has mixed wettability, which the changes on relative permeability may occur as there is an oil wet paths in large pore and causing the water flooding (Al-Garni & Al-Anazi, 2008). In order to have accurate measurement, it is stated that the native core is needed when the relative permeability is preserved.

- Saturation

  Wetting fluid and non-wetting fluid can be determined by the condition of saturation with addition of wettability. It could affect the relative permeability as saturation may impact the flow paths through the rock.

- Saturation history

  The history of fluid saturation can be differentiate into two, which are:

  a. Drainage

     A process when the oil is migrating to reservoir and displacing the water. It usually occurs when reservoir rock is 100% saturated and oil has not been accumulated, which will resulting on decreasing of saturation on wetting phase.

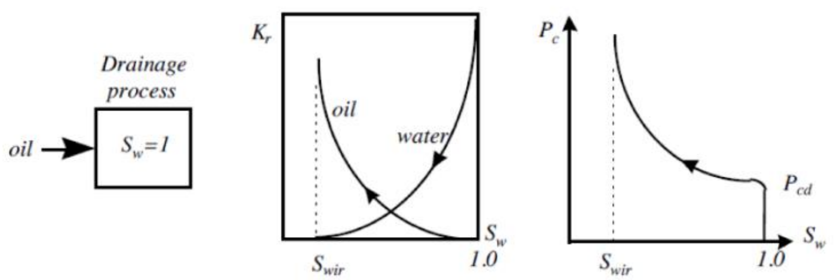

Figure 7: Drainage process [20]

  b. Imbibition

     This is the contrary of drainage process, where the water will displace the oil, which will increase the saturation of wetting phase.

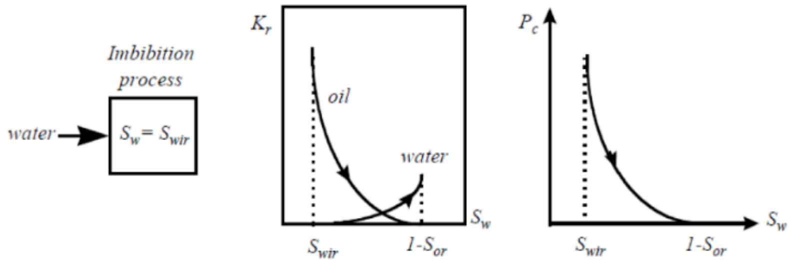

Figure 8: Imbibition process [20]

2.5 CAPILLARY PRESSURE

Capillary pressure is defined as the difference of existing pressure across curved interface of two immiscible fluids at equilibrium state.

$$P_c = P_{non-wetting} - P_{wetting}$$

It has several functions, including to estimate irreducible water saturation, residual oil saturation, water oil contact, hydrocarbon distribution in porous media, and oil recovery. Capillary pressure curves are reliant on direction of the saturation, which are imbibition and/or drainage. When the phenomenon is drainage process, capillary pressure usually tends to increase, and for imbibition, the contrary occur.

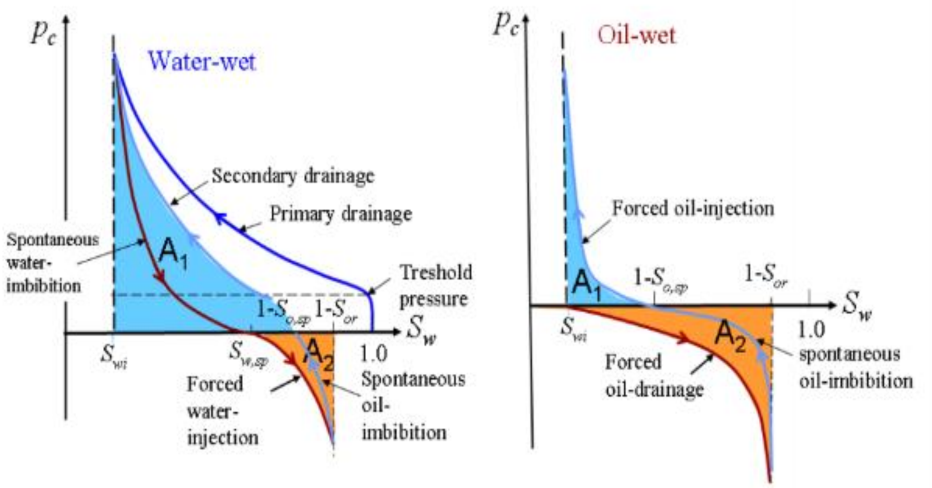

Figure 9: Typical capillary pressure curve on water-wet and oil-wet

Moreover, capillary pressure curves also able to determine the water oil contact, which occur when capillary pressure equals to pore entry pressure.

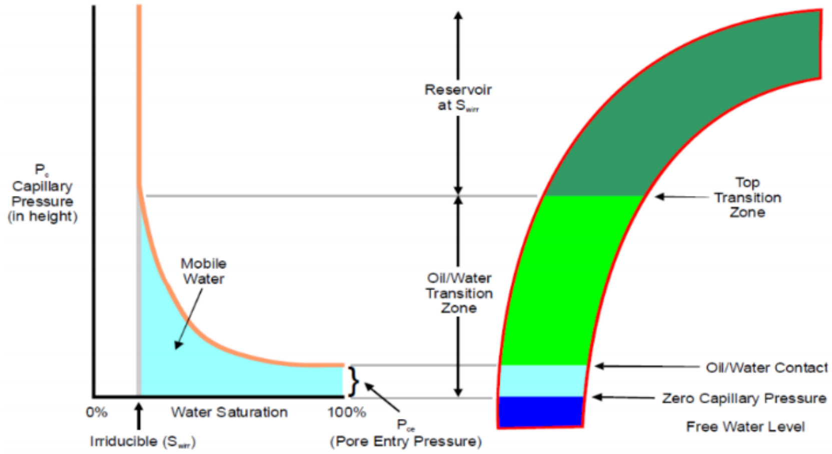

Figure 10: Capillary pressure for determining WOC

It is known that in uniformly wetted porous medium, when the wettability has small contact angles, capillary pressure become insensitive due to numerous factors, such as pore geometry effects and extremely rough surface. Meanwhile, when the cores have fractional or mixed wettability, oil wet and water wet distribution are the main point to determine capillary pressure curve, residual saturation, and imbibition behavior

2.6 CAPILLARY PRESSURE AND RELATIVE PERMEABILITY RELATIONSHIP

The relationship of capillary pressure and relative permeability is based on several equation. It has been derived from Kozeny equation together with tortuosity, electricity resistivity, and capillary tube model as factors that need to be considered. The classical one is by using Brooks-Corey-Burdine which wettability and pore size distribution are not linked. Brooks-Corey-Burdine equation can be described as follow:

$$k_{rw} = s_{ew}^4$$

$$k_{rnw} = (1 - s_{ew})^2\,(1 - s_{ew}^2)$$

$$s_{ew} = \frac{s_w - s_{rw}}{1 - s_{rw}}$$

where,

k_{rw} and k_{rnw} : wetting and non-wetting phase relative permeability

S_{ew} S_{rw} S_w : effective phase saturation, wetting phase residual saturation, and wetting phase saturation.

CHAPTER 3

METHODOLOGY

3.1 PROJECT MEHODOLOGY

This project was conducted based on the following activities towards the completion of FYP.

Figure 11: Research methodology stages

a) Research and Literature Review

The objective is to provide the better understanding and the description to minimize the scope work before the research begin. The activity is carried out through reading previous journal, textbook, articles, and other sources of research.

b) Proposal Writing

The objectives and problem statement are clearly stated in the proposal. The scope of study should be relevant and feasible within the given duration.

c) Case Study

Several studies will be conducted to analyze the measurement of wettability and wettability effects towards relative permeability and capillary pressure curves

d) Analysis

Collect and analyze the result of core test with different wettability and compared the result of capillary pressure and relative permeability for each rock wetting. Opinions will be given as the result after analyzing the case studies.

e) Evaluation

The final stage is to evaluate the best method in determining wettability and best potential condition of the reservoir based on surface wettability, capillary pressure, and relative permeability for reservoir evaluation.

3.2 KEY MILESTONE

For completion of this project, the following milestone should be completed at the end of the semester, as follow:

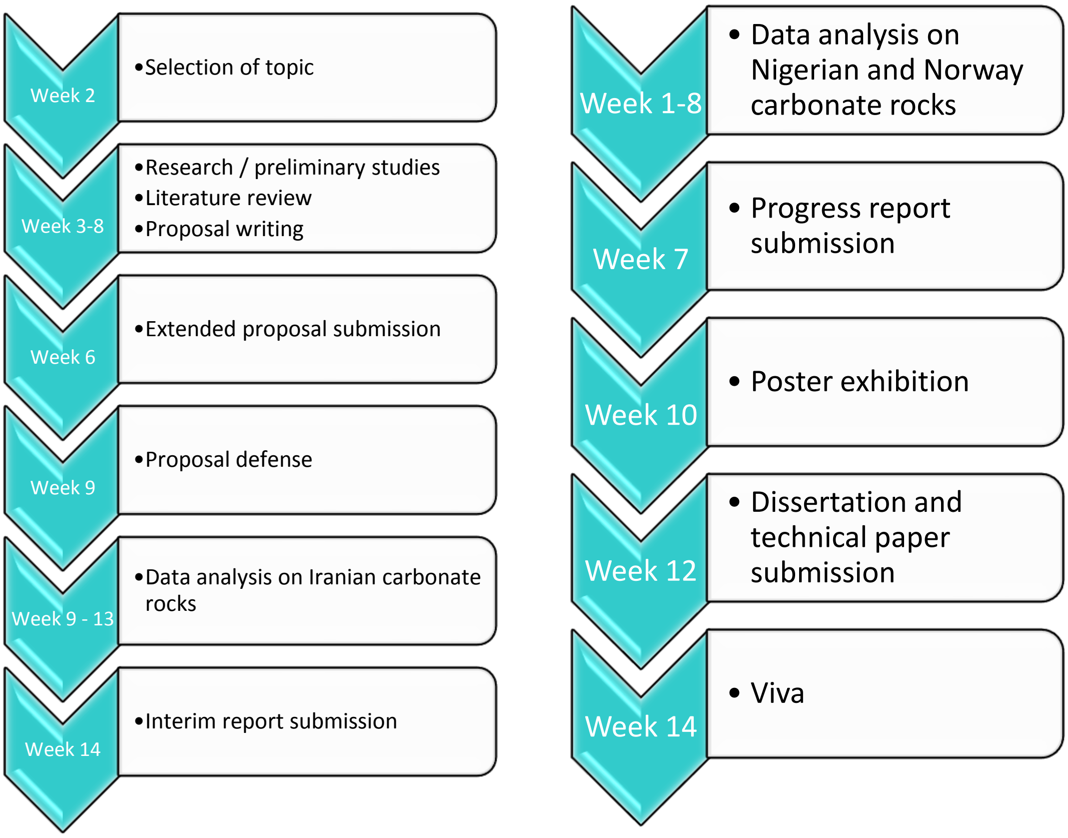

Figure 12: Key milestone FYP 1 & FYP 2

3.3 GANTT CHART

Table 2: Gantt chart FYP 1

Project Details	Weeks													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Selection of Topic														
Requirement Phase														
Problem Identification														
Preliminary Study on Project Background														
Define Objectives and Scope of Study														
Literature Review														
Project Analysis														
Research Findings														
Proposal Defense														
Data Analysis on CR-1														
Interim Report Submission														

Table 3: Gantt chart FYP 2

Project Details	Weeks															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Data Analysis on CR-2																
Data Analysis on CR-3																
Progress Report Submission																
Poster Exhibition																
Revision																
Dissertation and Technical Paper Submission																
Viva																
Dissertation Submission (Hard Cover)																

CHAPTER 4

RESULTS AND DISCUSSION

The results discussed below are based on experiments done previously by several researchers, in order to analyze the effect of wetting phase on relative permeability and capillary pressure curves from different carbonate rocks. Table below shows the comparison data from three different carbonate rocks formation and wettability experiment completed:

Table 4: Description of core sample analyzed

	CR 1 [22]	CR 2 [14]	CR 3 [6]
Origin of Core	Iran	Nigeria	Norway
Wettability Measurement	Relative Permeability; Amott/USBM method	Capillary Pressure using Centrifuge Method	Capillary Pressure
Core State Condition	Restore State Core	Restore State Core	Restore State Core

4.1 WETTABILITY EFFECTS ON CAPILLARY PRESSURE

The first study that will be analyzed is using CR-1, which the measurement of carbonate cores were done in order to measure the wettability index of each cores. The cores were restored, by placing cores into vacuumed apparatus, saturated with brine, and aged for around 40 days, to achieve better accuracy as it attains reservoir condition.

Core plugs were measured using Amott/USBM methods, which are combination of two quantitative methods, with the purpose of achieving more accurate measurements of wettability index. The following data shown the result from combination of Amott/USBM method:

Table 5: Combine Amott/USBM results on restored core plugs [20]

Field	Core ID	Swi (%)	Sor (%)	Amott WI			Combine Amott / USBM
				Iw	Io	I	
M	11	15.07	37.56	0.053	0.036	0.017	-0.545
	12	11.02	42.69	0.116	0.003	0.113	-0.339
	25	3.54	45.66	0.033	0.019	0.014	-0.452
	40	7.00	22.53	0.005	0.002	0.003	-0.395
	41	24.22	9.72	0.002	0.020	-0.018	-0.572
	42	10.00	34.26	0.030	0.003	0.027	-0.360
R	5	55.07	27.03	0.094	0.057	0.037	-0.310
	6	10.00	34.40	0.029	0.014	-0.115	-0.852
	13	39.81	35.19	0.167	0.074	0.093	0.374
	19	77.13	3.05	0.615	0.008	0.607	-0.098
	27	-	-	0.400	0.140	0.260	-

From the experiments data analyzed, the wettability index of each cores become one of the factors in order to determine the wetting phase of the reservoir. It is observed from the cores of field M, it has a tendency to be oil wet as the wettability index of these cores ranged from -0.3 to -0.6. Comparing these with cores of field R, the cores tend to have different wetting trends, which core #13 tends to be water wet core#19 tends to be intermediate, and the others are oil wet.

Moreover, while the capillary pressure curves are plotted, the wetting condition of the samples also could be indicated. As previously, it is mentioned that the wettability index is the factor of determining the wetting phase, the ratio between the areas under capillary pressure, drainage and imbibition, are actually the straight indicator of wettability degree. Therefore, to create the convenient scale of WI, the logarithm of area is calculated. In order to identify the different hysteresis of capillary pressure at different wetting phase, the graphs of each cores are presented as follow:

4.1.1 Oil Wet

The figures below show the behavior of capillary pressure curve while the core is under oil wet condition. The WI ranged for oil wet is in negative value, between -0.3 to -1, which cause the area of imbibition is larger than drainage area.

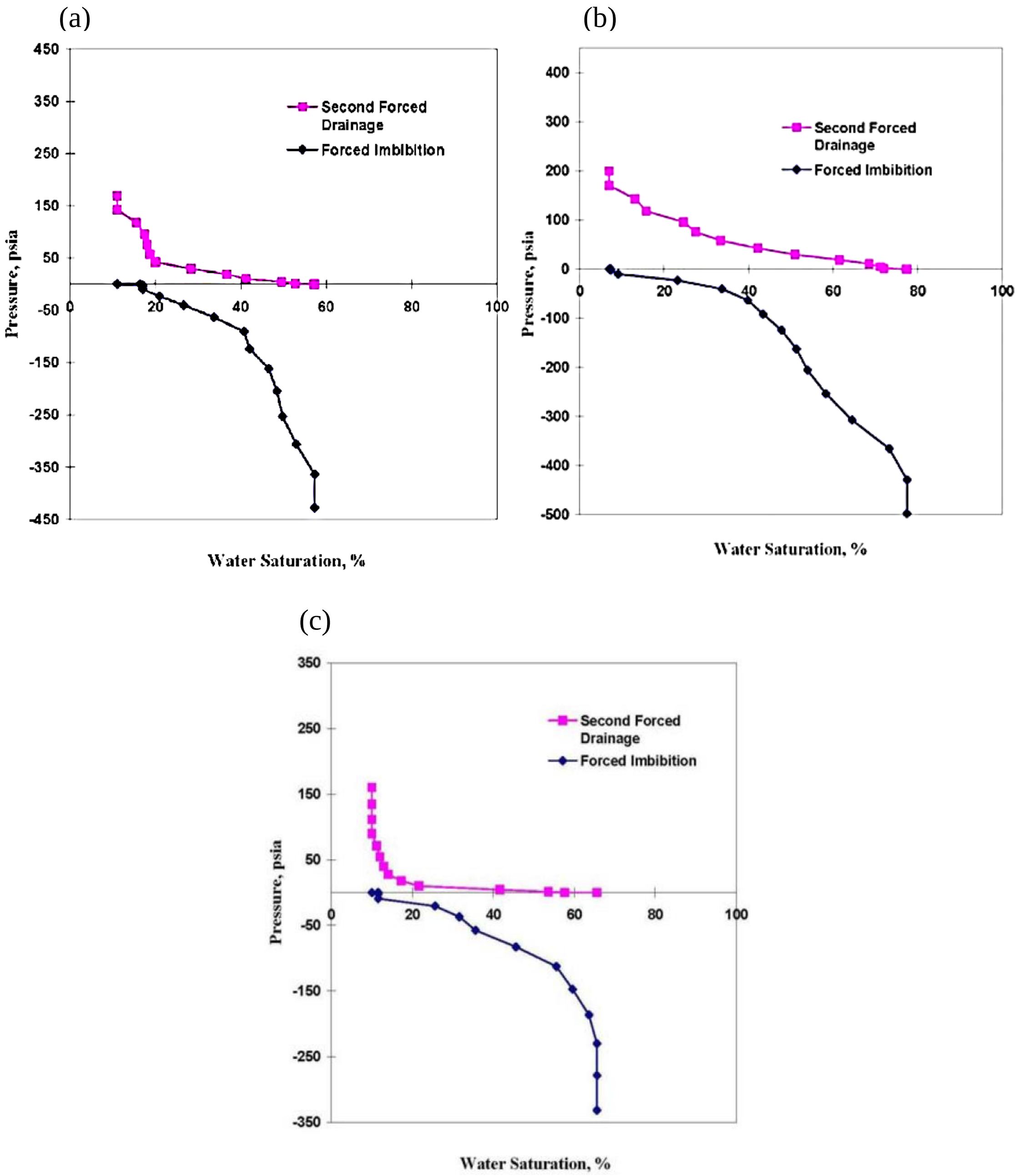

Figure 13: Capillary pressure curves for sample 12 (a), 40 (b), 6 (c) [22]

4.1.2 Water Wet

In contrast, as one of the cores from field R indicates to be water wet, the capillary pressure curve of this core shows that the area of drainage is bigger than the area of imbibition. This ratio will create the wettability index tends to be positive value, ranged between +0.3 to +1.

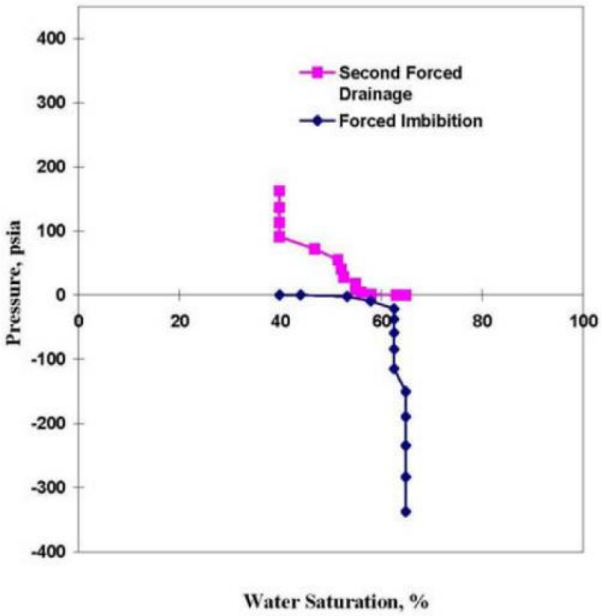

Figure 14: Capillary pressure curve for sample 13 [22]

4.1.3 Intermediate Wet

Intermediate wet is identified as the condition of rock where there is no preference for water and oil. It also shows that the capillary pressure curve will have slightly same area of drainage and imbibition which resulting the WI for intermediate wet near zero.

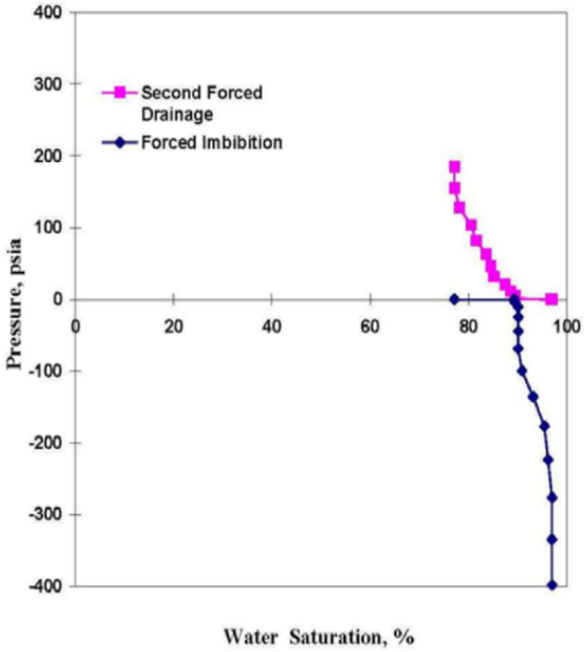

Figure 15: Capillary pressure curve for sample 19 [22]

Comparing the condition of CR-1, carbonate rocks 2 (CR-2) experiment which was done recently in 2014, have initial condition as water wet. Firstly, the cores were experimentally measured by routine core analysis, to determine core properties including porosity, permeability, and saturation.

In addition of routine core analysis, special core analysis (SCAL) was also conducted in order to measure capillary pressure using porous plate method. Porous plate was being used, as recently, it is found to be reliable and less experimental error compared to other methods, mercury injection and centrifugation techniques. The capillary pressure was being measured under different wettability condition, which the original condition or water wet and after alteration or oil wet. Below tables show the data of conducted experiments.

- Air – Brine

Table 6: Air-brine capillary pressure results [14]

Pc (psi)	Sw (%) Sample 102	Sw (%) Sample 546	Sw (%) Sample 84	Sw (%) Sample X
1	98.39	98.24	98.25	99.05
2	90.90	91.85	91.19	91.94
5	80.06	80.02	82.06	82.61
8	62.72	63.19	65.71	67.19
15	43.22	41.77	42.54	48.77
35	19.13	15.93	13.17	20.79

- Air – Oil

Table 7: Air-oil capillary pressure results [14]

Pc (psi)	So (%) Sample 102	So (%) Sample 546	So (%) Sample 84	So (%) Sample X
1	98.90	98.22	98.56	100
2	96.16	93.65	94.94	98.40
5	90.51	85.57	86.76	90.64
8	81.24	71.85	70.95	81.36
15	60.45	50.24	51.61	62.72
35	29.13	26.37	24.72	34.00

Analyzing two different wetting condition of these cores, water saturation showed different value while tested at same capillary pressure. The unmodified cores or water wet condition have saturation ranged from 13 – 21% meanwhile the modified cores or oil wet condition ranged from 24 – 34%.

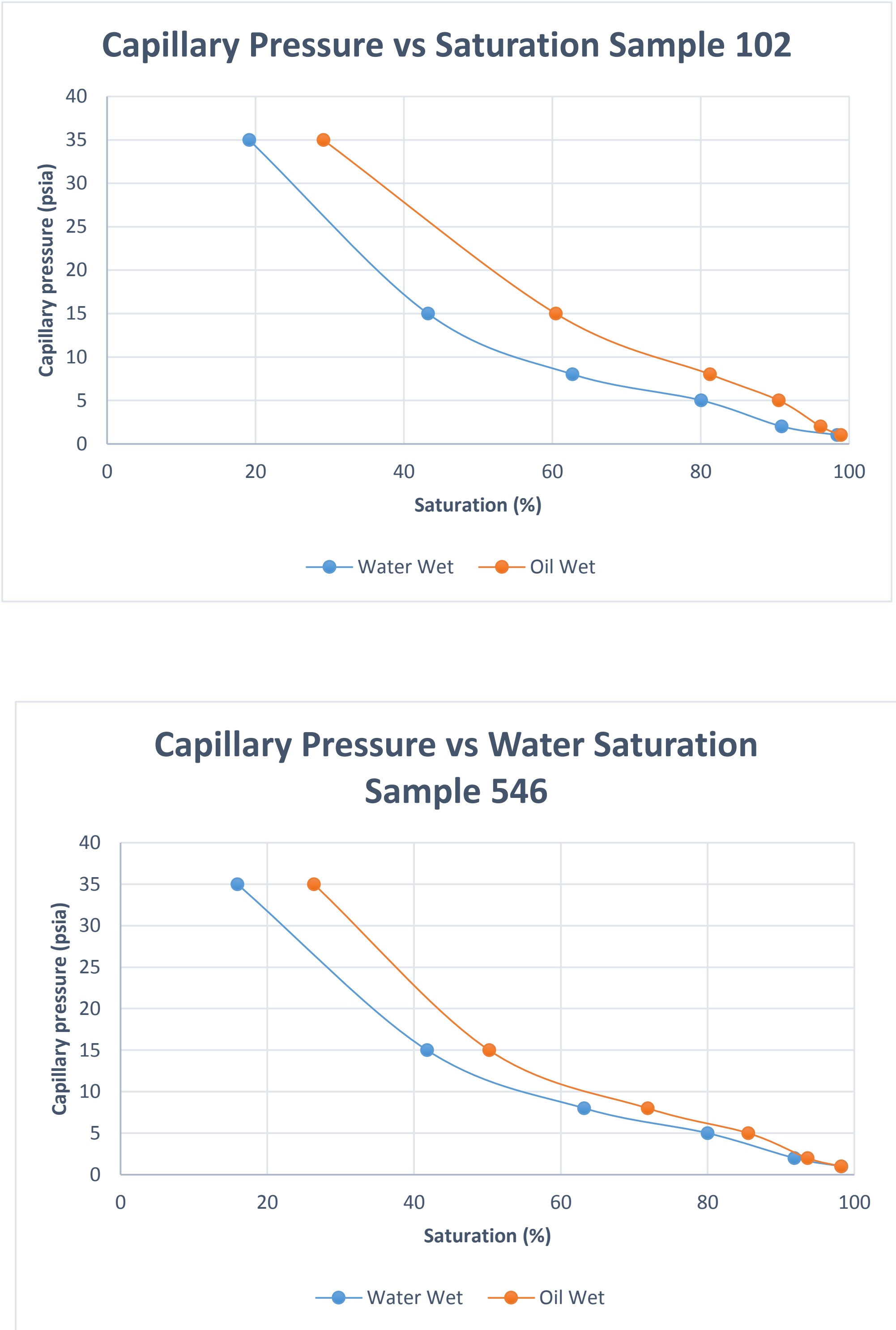

Figure 16: Capillary pressure curves for sample 102 and 546 [14]

As it was mentioned that capillary pressure curves are able to determine several factors, such as to estimate irreducible water saturation, residual oil saturation, water oil contact, hydrocarbon distribution in porous media, and oil recovery. From the CR-1 data, it shows that the water flooding for water wet will provide better result compared to oil wet condition. Moreover, from CR-2, observation of Lambda (1/slope), which able to determine the types of reservoir either clean sand or shaly reservoir. The indication is based on value of irreducible water saturation, in which the lower value indicates clean sand reservoir with high permeability. Oppositely, when the irreducible water saturation shows higher value, it indicates shaly or silty reservoir with low permeability.

Furthermore, the experiments done on carbonate rock done in Norway also being analyzed. The result of the special core analysis shows the tendency of carbonate rock to be oil wet as the capillary pressure curve provides the larger area of imbibition compared to drainage.

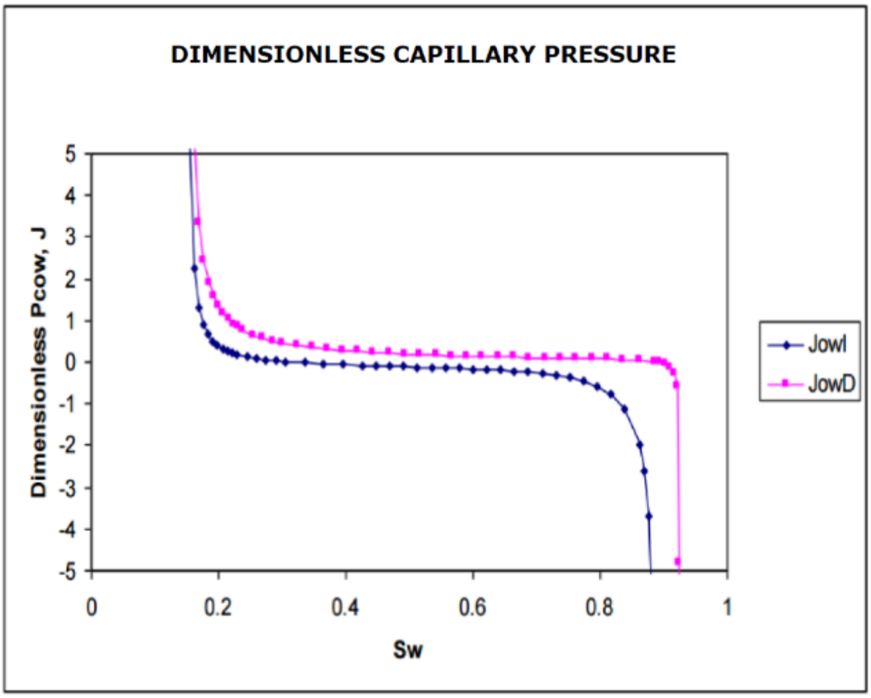

Figure 17: Capillary pressure curve of sample CR-3 [6]

In summary, the hysteresis of capillary pressure curves in different wetting phase, show different tendencies that briefly explain in table below:

Table 8: Differences on hysteresis of water-wet and oil-wet

Water Wet	Oil Wet
• Positive WI (+0.3 to +1.0) • Larger drainage areas that shows recovery improvement can be done by waterflooding. • Lower irreducible water saturation, that give tendencies of clean sand reservoir with high permeability	• Negative WI (-0.3 to -1.0) • Larger imbibition area, means that waterflooding, as a method of recovery improvement, will not perform as good as in water wet condition. • Higher irreducible water saturation, give tendencies to be shaly reservoir with low permeability

4.2 WETTABILITY EFFECTS ON RELATIVE PERMEABILITY

Relative permeability hysteresis is being analyzed by firstly using CR-1, which the cores from field M that known to be oil wet, graphs of each cores tend to have same hysteresis. The data of the relative permeability experiments are shown as follow:

Table 9: End point values and crossover saturation [22]

Field	Core ID	Swi (%)	Kro (Swi)	Sor (%)	Krw (Sor)	Sw @Krw=Kro
M	11	22.6	0.65	27.4	0.095	41
	12	20.4	0.94	28.2	0.106	46
	25	14.2	0.93	29.9	0.205	33
	40	17.3	0.54	30.5	0.148	42
	42	18.2	0.64	43.4	0.085	35

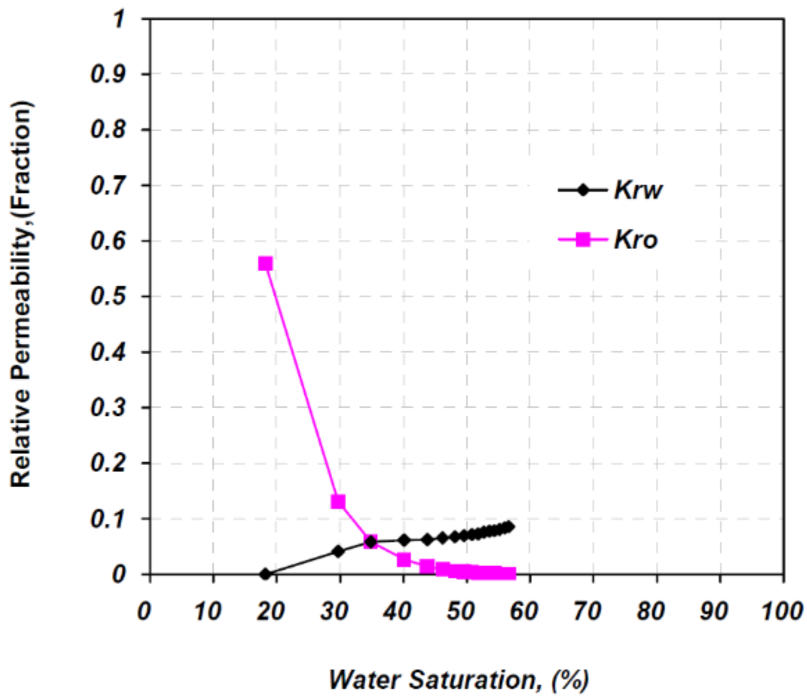

Figure 18: Relative permeability curve result [22]

As showed from table and figure above, it can be seen that the crossover saturation of all the cores of field M have value less than 50%, which based on Craig's rule of thumbs, it is an indication for oil wet. However, other rules did not satisfy by the cores which conclude that solely qualitative experiment will not be accurate, instead quantitative experiment is needed (Cueic).

Comparing the experiments done of CR-1, results of CR-2 shows one of the way to calculate relative permeability by using Brooks – Corey – Burdine formula, which related with capillary pressure values, as follow:

Table 10: Air-brine relative permeability results [14]

Core	P (psia)	Sw (%)	Sw* (%)	Krw	Kra
102	1	98.39	98.01	0.92271	0.0000156
	2	90.90	88.75	0.62033	0.0026893
	5	80.06	75.34	0.32224	0.0262846
	8	62.72	53.90	0.08441	0.1507675
	15	43.22	29.79	0.00787	0.4492212
	35	19.13	0.00	0.00000	1.0000000
546	1	98.24	97.91	0.91885	0.0000182
	2	91.85	90.31	0.66506	0.0017338

	5	80.02	76.23	0.33775	0.0236566
	8	63.19	56.22	0.09986	0.1311285
	15	41.77	30.74	0.00892	0.4344236
	35	15.93	0.00	0.00000	1.0000000
84	1	98.25	97.98	0.92179	0.0000162
	2	91.19	89.85	0.65185	0.0019831
	5	82.06	79.34	0.39623	0.0158175
	8	65.71	60.51	0.13405	0.0988536
	15	42.54	33.82	0.01309	0.3878143
	35	13.17	0.00	0.00000	1.0000000
X	1	99.05	98.80	0.95288	0.0000034
	2	91.94	89.82	0.65100	0.0019999
	5	82.61	78.05	0.37102	0.0188404
	8	67.19	58.58	0.11775	0.1126997
	15	48.77	35.32	0.01557	0.1126997
	35	20.79	0.00	0.00000	1.0000000

Table 11: Air-oil relative permeability results [14]

Core	P (psia)	So (%)	So* (%)	Kro	Kra
102	1	98.90	98.45	0.93935	0.0000074
	2	96.16	94.58	0.80025	0.0003095
	5	90.5	86.61	0.56268	0.0044807
	8	81.24	73.53	0.29230	0.0321872
	15	60.45	44.19	0.03814	0.2506098
	35	29.13	0.00	0.00000	1.0000000
546	1	98.22	97.58	0.90675	0.0000279
	2	93.65	91.38	0.69715	0.0012276
	5	85.57	80.40	0.41790	0.0135793
	8	71.85	61.77	0.14557	0.0903991
	15	50.24	32.42	0.01105	0.4087206
	35	26.37	0.00	0.00000	1.0000000

84	1	98.56	98.09	0.92565	0.0000139
	2	94.94	93.28	0.75705	0.0005869
	5	86.76	82.41	0.46128	0.0099238
	8	70.95	61.41	0.14223	0.0927539
	15	51.61	35.72	0.01628	0.3604722
	35	24.72	0.00	0.00000	1.0000000
X	1	100	100.00	1.00000	0.0000000
	2	98.4	97.58	0.90650	0.0000281
	5	90.64	85.82	0.54240	0.0053001
	8	81.36	71.76	0.26514	0.0386921
	15	62.72	43.52	0.03586	0.2586388
	35	34	0.00	0.00000	1.0000000

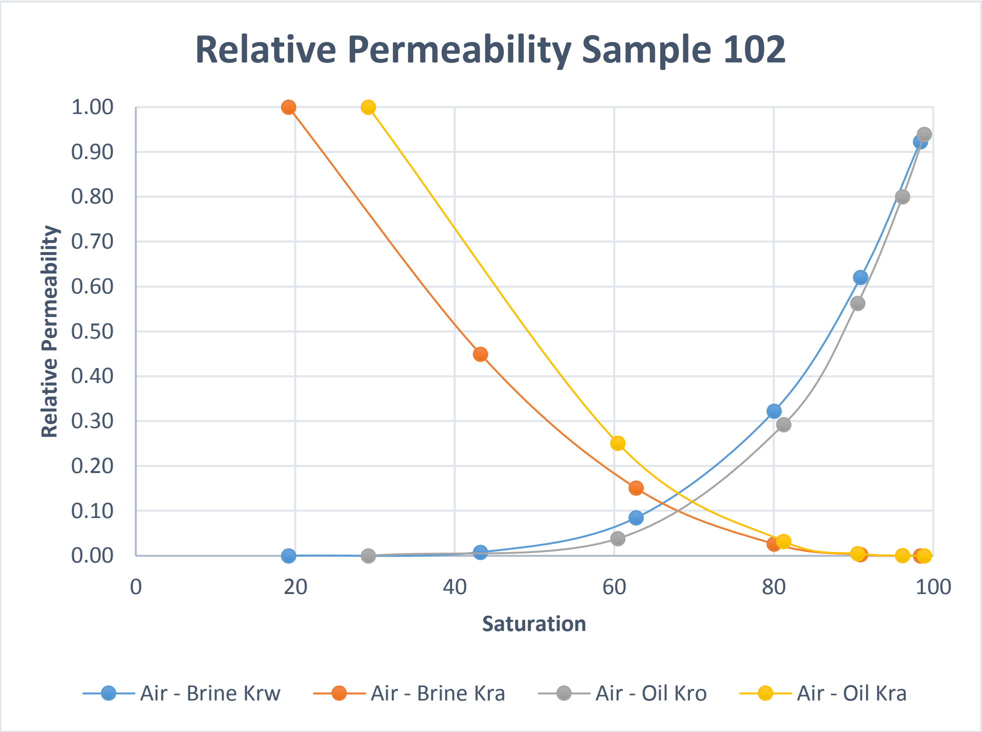

Figure 19: Relative permeability curve of sample 102 [14]

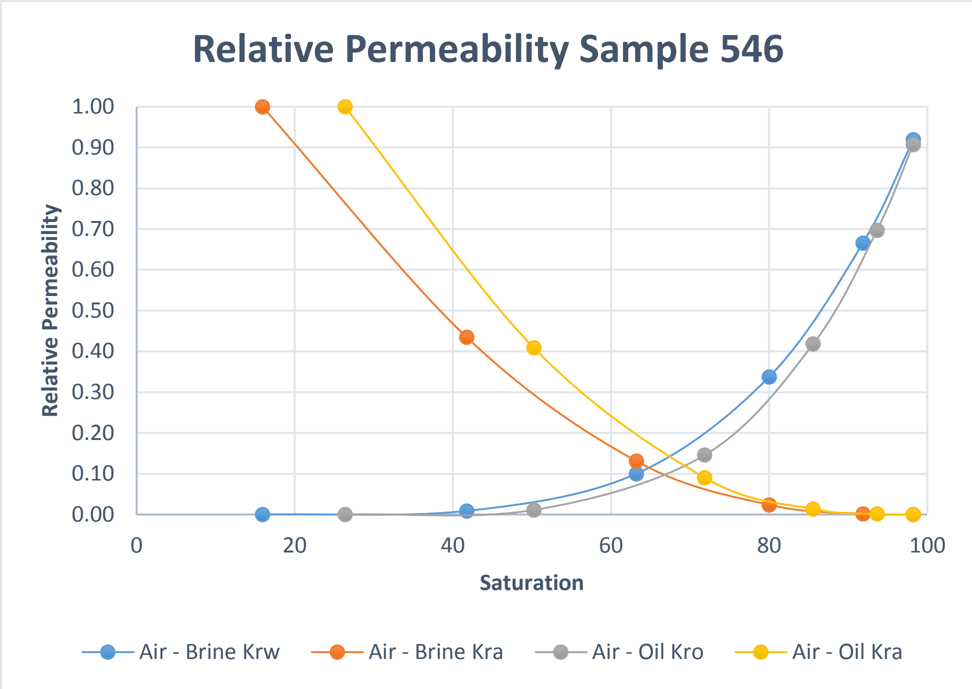

Figure 20: Relative permeability curves of sample 546 [14]

As it could be seen from the results and the graphs, it showed different trends of relative permeability curves that did not satisfy Craig's rules of thumbs. Based on Craig's rules of thumbs that the saturation at which wetting phase and non-wetting phase relative permeability are equal for water wet should be greater than oil wet. However, in this experiment, the contrary occur. It also shows that the interstitial water saturation for water wet is lower than oil wet. However, observing from the graph of relative permeability for modified cores and unmodified cores, it can be identified that the relative permeability of oil at air-oil condition is slightly higher than relative permeability of water at air-brine condition at residual oil saturation. This hysteresis occurs as the wetting phase in oil wet condition or modified cores, expected to flow easier than the wetting phase in water wet condition.

Moreover, when experiment of CR-3 are being analyzed, the relative permeability curve shows the tendency of oil wet condition. It can be identified that as water flow through large pores, relative permeability of water increase rapidly and relative permeability of oil starts to decrease. It shows that the two phase region are larger which the improvement of recovery can be done by using surfactants, as one of the method.

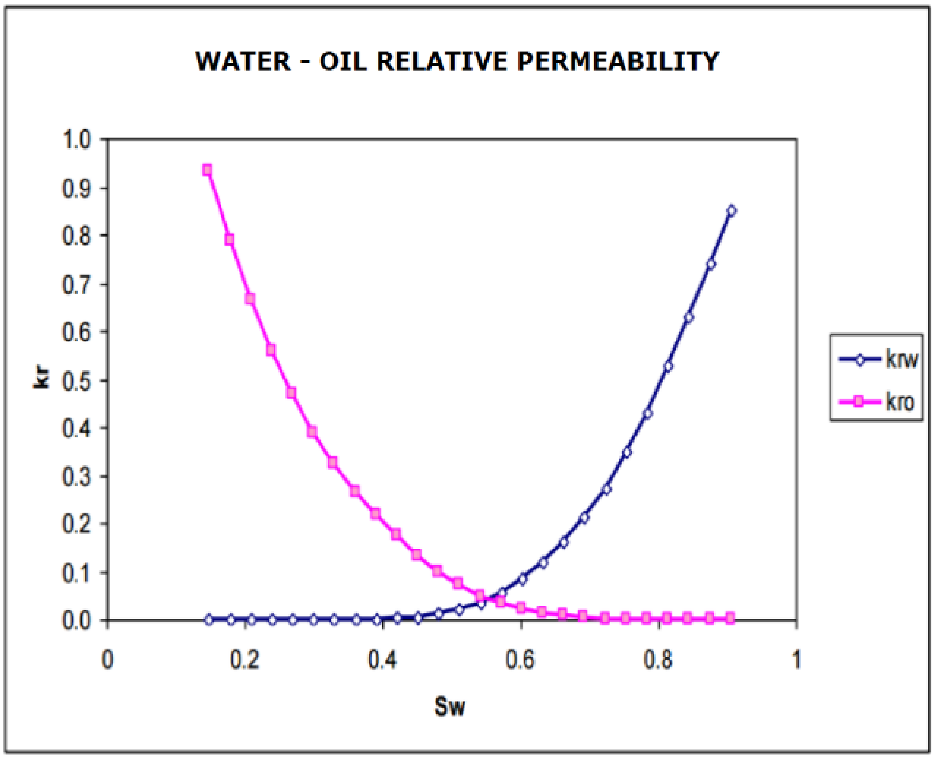

Figure 21: Relative permeability curve of sample CR-3 [6]

In summary, the different hysteresis of relative permeability curves for water wet and oil wet condition are shown in table below:

Table 12: Hysteresis difference of relative permeability curve on water-wet and oil-wet

Water Wet	Oil Wet
• Higher irreducible water saturation, which the wetting phase usually has not flow. • Water tends to displace oil as water saturation increases and oil saturation decrease. • Flood of the system usually have low rate as the energy provides by capillary forces.	• Lower irreducible water saturation • Larger pores will let water to flow as relative permeability of non-wetting decrease and relative permeability of wetting phase increases rapidly.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

There is one main objective to be completed through FYP 1 and FYP 2, which is to analyze the effect of different wetting phase toward relative permeability and capillary pressure. As the analysis studies are made based on three differents origin of carbonate rocks, each rocks show different trends of the curve. By identifying wettability index, resulting from combine Amott/USBM method, the wetting condition of the cores can be determined, which will give more accurate result as an addition to qualitative methods. When the condition of the reservoir tends to be water wet, it can be identified by several factors. Firstly, the wettability index that ranged from +0.3 to +1.0, which also can be identified by larger area of drainage. As in drainage is known as a process of oil migrates to reservoir, by which means to improve recovery, water-flooding is one of the method as it may push away the oil that located in center of pores. In contrast, oil wet condition shows the opposite tendency, which imbibition area is larger than drainage area. The drainage curve in oil wet condition tends to be slightly flat line, which indicates oil behavior will enter spontaneously as water need to displace oil. Moreover, analyzing from capillary pressure curve, the observation of Lambda shows that water wet condition tend to have lower irreducible water saturation resulting lower value of Lambda.

Furthermore, for relative permeability curve, it also shows different trend for different wetting phase. For water wet condition, the saturation at which relative permeability of wetting phase and non-wetting phase are equal should be higher than in oil wet condition. However, in experiments done by MR et. al., the hysteresis occurs contrarily. The difference of hysteresis in different cores samples that have been experimented showed that in order to have better accuracy for determining wettability of the rock, measurement with solely method is not sufficient. From three of the cores samples that have been analyzed, most of the cores are categorized to be oil wet as it the curves hysteresis show the tendencies of oil wet. It also satisfy the origin of carbonate rocks, which it was discussed having oil wet condition.

5.2 RECOMMENDATION

The difference and inaccuracy of the measurements are occurred may due to several limitations. First that the different types of rocks and condition of cores when it was being experimented. Other than that, the original location on where the location of the rocks also may affect as each reservoir has different temperature. Another concern is limitation of the methods on experiments done, which may create inaccuracy.

Hence, for improvement in the future, experiments should be done with various methods with equal condition of the cores, whether it is native state or restored state. Various methods of wettability test also should be done for better investigation of fluid flow properties, including relative permeability and capillary pressure. In addition, several types of cores should be also utilized to understand different hysteresis that would occur if the experiments are tested on cores from different types of reservoir rocks.

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