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# WATERFLOOD SUSCEPTIBILITY OF NGRAYONG SANDSTONE RESERVOIR IN "X"-WELL, XYZ FIELD, EAST JAVA

## *WATERFLOOD SUSCEPTIBILITY* PADA RESERVOIR BATUPASIR NGRAYONG DI SUMUR-"X", LAPANGAN XYZ, JAWA TIMUR

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***ABSTRAK***

*Struktur-struktur antiklinorium yang terbentang di daerah Zona Rembang Jawa Tengah hingga Jawa Timur mencerminkan perangkap minyak yang berada di bawah permukaan. Lapangan-lapangan minyak ini sudah dieksploitasi kandungan minyaknya sejak jaman Belanda dimana pada saat ini kandungan water cut sudah di atas 95%. Dari interpretasi cadangan dan produksi yang dilakukan oleh banyak peneliti, diperkirakan minyak yang tersisa masih berada di kisaran 50% (OOIP). Untuk mengatasi hal tersebut akhir-akhir ini pemerintah mendorong para peneliti agar melakukan kajian pada lapangan-lapangan minyak di zona tersebut dalam rangka peningkatan perolehan minyak secara menyeluruh dengan target perolehan minyak yang sebesar-besarnya. Lapangan minyak XYZ yang berada di Zona Rembang mempunyai reservoar batupasir yang penyebarannya cukup luas di daerah perbatasan Jawa Tengah – Jawa Timur. Batuan reservoir di daerah ini merupakan batupasir berbutir halus yang mengandung matrik gampingan dan lempungan. Mineral lempung hampir terdistribusi merata dengan kandungan kaolinit yang cukup tinggi (30% dari kandungan mineral lempungnya). Kaolinit merupakan mineral yang mudah terlepas oleh adanya aliran fluida sehingga akan menjadikan masalah sewaktu proses produksi berlangsung. Air injeksi dari beberapa sumur mengandung komposisi yang juga memudahkan terbentuknya slug dan scale seperti dijumpainya kandungan crude oil serta bakteri yang bersifat korosif sehingga cenderung memudahkan terbentuknya kerusakan formasi dan korosi pada peralatan pemboran maupun produksi. Sesuai dorongan pemerintah, studi ini dilakukan untuk melakukan percobaan dalam meningkatkan perolehan minyak dengan menggunakan metode waterflooding. Untuk menghindari terjadinya aliran non-Darcy dilakukan analisis Kecepatan Aliran Kritis (Critical Velocity) dimana hasilnya diperoleh = 37.6 ft/day, yang ditetapkan sebagai kecepatan pendesakan air injeksi maksimum dalam percobaan waterflooding. Berdasarkan percobaan waterflooding dalam sekala laboratorium pada Sumur-X, pendesakan minyak dengan air injeksi tanpa ditambah bahan aditif menghasilkan peningkatan perolehan minyak sebesar 0.77% Pore Volume (0.77%PV), sedang jika air injeksi ditambah bahan aditif peningkatan perolehan minyak dapat mencapai 1.31%PV.*

***Kata Kunci****: waterflooding susceptibility, kecepatan alir kritis, peningkatan perolehan minyak.*

**ABSTRACT**

Antiklinorium structures that are spreading in the area of Rembang Zone along the Central Java to East Java reflect oil traps that lay under the surface. The oil fields have been exploited since the time of the Dutch occupation leaving the water cut at above 95%. Interpretation of reserves and production forecasts made by many researchers conclude that the remaining oil is still in the range of 50% (OOIP). To overcome the problem, the Government recently encouraged researchers to conduct a comprehensive review in terms of enhanced oil recovery with the goal of increasing the oil recovery in this zone by as much as possible. The XYZ-oil field in the Rembang Zone has a widely spread reservoir sandstone in the border area of the Central Java - East Java. Reservoir rocks in this area contain calcareous and silty matrix. Clay minerals are distributed almost evenly with high kaolinite content (30% of the bulk clay mineral). Kaolinite is a mineral that is easily removed by fluid flow so that it would create problems during the oil production process. The composition of injection water collected from several wells can also easily form slugs and scale as indicated by the occurrence of crude oil and bacteria that behave as a very corrosive substance that tends to facilitate the creation of production and equipment damage. This study conducted an experiment in enhanced oil recovery using waterflooding. To avoid the occurence of non-Darcy flow, critical velocity analysis was conducted obtaining a value of 37.6 ft/day. This velocity is defined as a maximum injection velocity of the water displacement in this waterflooding experiment. Based on the waterflooding experiment of X-Well in the laboratory, the injection of oil using injection water without additives led to an increase in oil recovery of 0.77% Pore Volume (%PV), while the displacement of injection water added with additives resulted in an increase in oil recovery by as much as 1.31%PV.

**Keywords:** waterflooding susceptibility, critical velocity, enhanced oil recovery.

## I. INTRODUCTION

Oil wells in Indonesia which commenced production in the late 1980s almost entirely have been in a state that cannot be produced by primary recovery. In other words, the wells have been already decreasing their reservoir pressures with the result that the oil cannot be produced by a natural drive that comes from the reservoir itself, although aided by artificial lift. Therefore, it is necessary to find a technological application to drain the residual oil saturation in order to get as much oil as possible.

The oil reserves in the reservoir rock cannot entirely be produced. Some oil is left inside the reservoir rock which is referred to as residual oil saturation. The residual oil is caused by many factors including the characteristics of reservoir rock, the wettability nature of the rock, permeability, interconnected pores within the rock, and the errors in producing the oil, as well as other factors that commonly occurred in old wells as the result of declining reservoir pressure (depleted reservoir).

Based on The APEA Journal (1978) production of oil from the reservoir to primary energy on average can only obtain around 30% of the amount of reserves. For example in the United States in 1976, at that time only about 20% of oil reserves could be produced at an early stage with primary energy (water drive). Then about 15% of oil can again be produced by means of secondary recovery or with enhanced oil recovery. The remaining amount of more than 50% cannot be produced, and this remaining residual oil is called dead oil.

An XYZ Oil Field in East Java is an old oil field discovered by Dutch Petroleum Company in 1893 where the first oil well was drilled in this field 32 years later (1925). The average depth of hundreds of oil wells in this area was only about 500 meters. Given the condition of oil wells, they can still be expected to improve their oil recovery, therefore a study of how to exploit the remaining oil as much as possible is indispensable. Injection water is a relatively inexpensive technology application in an effort to produce as much of the remaining oil in the reservoir rock by injecting water into the reservoir rock.

Pertaining to government encouragement in enhancing the oil recovery in the depleted oil field, the author conducted a study of Well X, XYZ Field, East Java. The study is based on core samples of rock and crude oil taken from the oil field. The method for increasing the oil recovery used waterflooding susceptibility and the research was conducted at the LEMIGAS Exploitation Laboratory.

The aim of the study is to undertake the waterflood susceptibility in the laboratory by evaluating the compatibility of two different forms of water which were injected to the sandstone reservoir rock samples saturated with oil. The result of the two different injections of water were compared and calculations made as to which water injection will provide a higher oil recovery.

## II. FIELD REVIEW

The XYZ field is an oil field which is located in the Rembang Zone, in the northern part of North East Java Basin. Rembang Zone is mountainous folds in the form of anticlinorium that extends from the west to the east, from Purwodadi through Blora, Jatirogo, Tuban to Madura Island.

In general, the geological conditions of the XYZ Field area is an anticline structure with an axis of northwest – southeast direction, which is a part of Anticlinorium Rembang in the Northeast Java Basin. According to Netherwood (2000), such anticlines were intensively asymmetrical faulted with a slope of 10 - 15$^o$ towards the northeast and 60$^o$ to the southwest (Figure 1).

According to Yudha (2003), to date 167 wells have been drilled, whereas 42 wells still provide

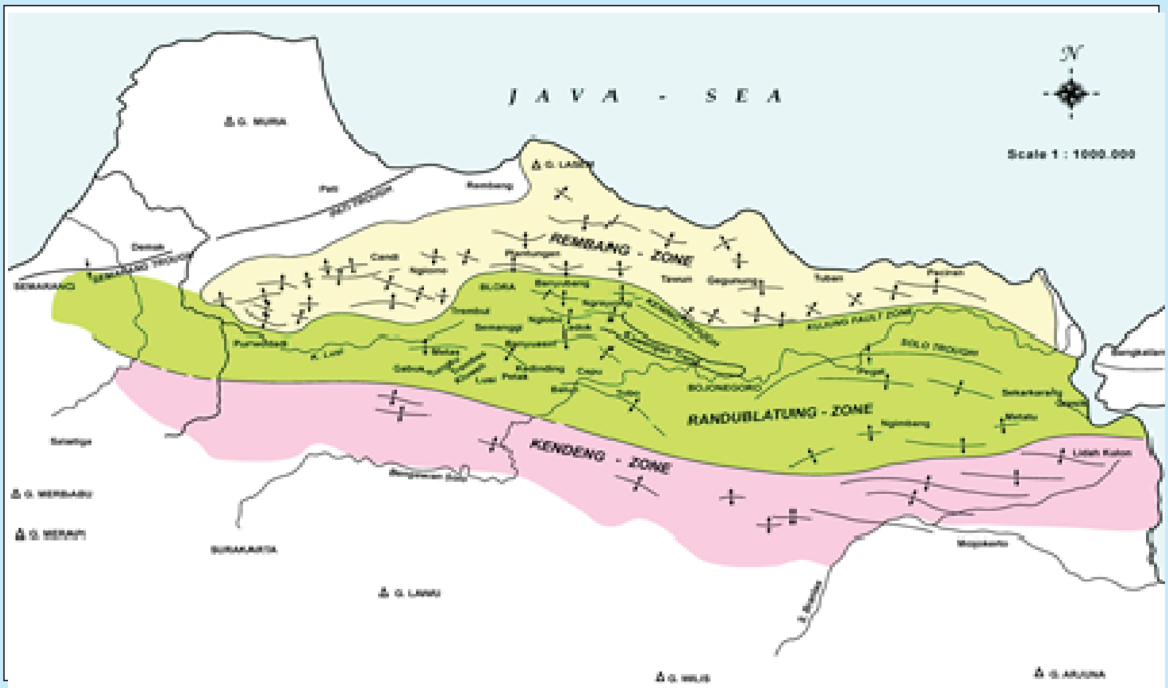


**Figure 1**
**Fisio-tectonostratigraphy of North East Java Basin.**

oil production from the reservoir sandstones of Ngrayong Formation. Based on Yudha's calculation, the remaining reserves from this formation is about 35 million barrels.

The reservoir sandstone of Ngrayong Formation in the XYZ Field is lithologically dominated by quartz sandstones, massive, occasionally with cross bed structure, composed of alternating sandstone and silt, fine sandstones and black shale with carbonate granules.

## A. Stratigraphy

East Java Basin, according to Peter, L., (1991) is divided into three member structures i.e. from north to south: Northern Platform, Central High and Southern Basin. The Northern Platform is composed of Bawean Arc and Madura/Kangean Platform. The Central High consists of Kujung, Madura, Kangean and Lombok Highs, while to the south the Southern Basin is divided into three zones, i.e. Rembang, Randublatung and Kendeng zones respectively.

The area studied is located in the southern part of Rembang Zone which stratigraphically is based on lithofacies consisting of Ngimbang Clastics at the bottom, Lower Ngimbang Shale, Upper Ngimbang Shale, Kujung, Tuban, Wonocolo, and Lidah at the top (Figure 2). From Figure 2, oil containing reservoir in Rembang Zone can be seen coming from the following Formation: Lidah at the top, Ledok, Ngrayong, Tuban, Top Kujung, and Top Ngimbang.

Ngrayong Formation is generally recognised as the sequence of quartz sand rich beds in the lower part of the Wonocolo Formation (Lunt 1991). This formation consists of sandstone with claystone intercalation, marl, and orbitoidal limestone. Ngrayong Formation was deposited conformable and overlies the Tawun Formation. The sandstones are red to yellowish red in color, showing a soft sediment deformational structures and scattered vertical burrows of Ophiomorpha. Based on paleontological analysis, this formation indicates N9-N12 (Middle Miocene) in age (Awang 2004). From geological section, the thickness of Ngrayong Formation is about 300 to 500 m. In excess of 150 MMBO have been produced from the Ngrayong Sandstones (Ardhana 1993).

## B. Reservoir Rocks of the XYZ Field

The reservoir rock taken from a depth interval of 825 - 830 metres is sandstone containing mineral carbonate rocks and debris - so-called calcareous sandstones - which dominates the rock lithology of the Middle Miocene Ngrayong Formation.

According to Yudha Prakasa (2003) the XYZ Field is the oil production structure discovered in

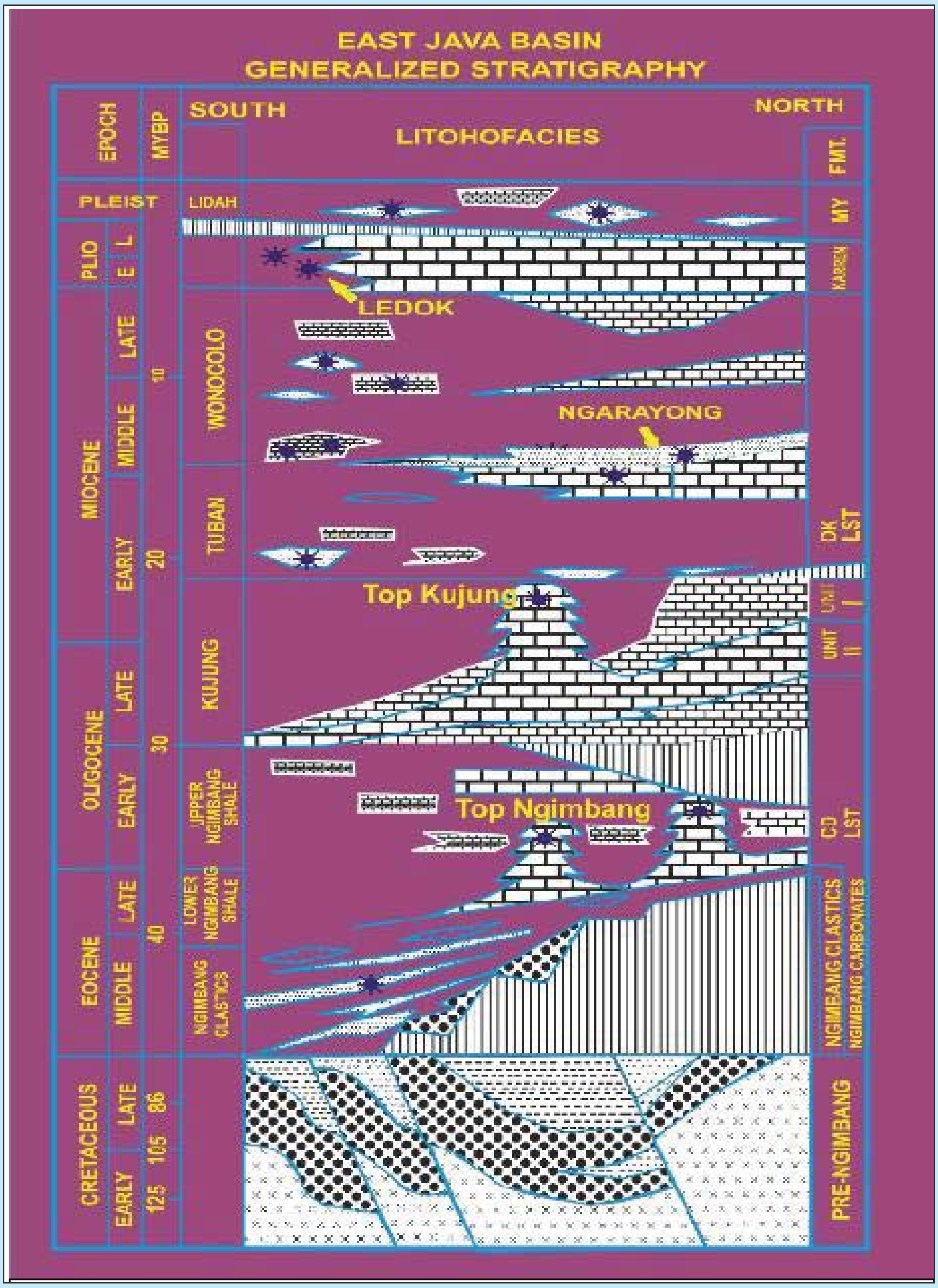


**Figure 2**
**Java Basin - Generalized stratigraphy (Lunt P. 1991).**

the 1920s where the oil is produced from Ngrayong Formation. Ngrayong Formation is lithologically composed of calcareous sandstones, silty sandsones and sandy limestones alternating with silts and black shales with a little bioturbation structure.

### C. Basic Parameters of Reservoir Rocks

The basic parameters of the reservoir rock are the properties of the rock formations such as porosity, permeability, fluid saturation, wettability, and compatibility as well as critical velocity which were measured, evaluated and used in this study.

**Wetting properties of rocks (wettability)**

Wettability can be defined as the ability of a fluid to wet the surface of a solid or a rock, because of the influence of the forces of the interfacial tension, i.e., molecular tension between fluids and solids.

**Relative Permeability**

The relative permeability is the ratio of an effective permeability to the absolute permeability, denoted as $k_{rw}$ (relative permeability of water) or $k_{ro}$ (relative permeability of oil) or $k_{rg}$ (gas relative permeability) to air permeability (absolute) denoted as $k_a$.

**Water-Rock Compatibility**

Analysis of water compatibility against the rock was conducted to observe if the water when it is injected into the reservoir rock will affect the properties of rock by the process of the interaction between water and rock. If the water after being injected into the rock affects the properties of the rock such as decreasing its permeability, the relationship of water and the rock are referred to as incompatible, and vise versa if the injected water does not affect any of the properties of the rock it is termed compatible (Core Laboratories 1972).

**Critical Flow Velocity (Critical Velocity)**

Critical Velocity is established by constructing a graphic of permeability versus interstitial velocity of fluid flow. The critical flow rate is obtained when permeability of the liquid reaches the highest point, where if the flow rate is increased the permeability will begin to decline (Sinclair and Duguid 1990). Relating to the type of flow, fluid flow below the point of critical velocity is laminar while after that the flow changes to turbulent resulting in migration of fine particles towards the well bore.

**Waterflood Susceptibility (WFS)**

Waterflood susceptibility is the concept of displacement of fluid with water. The term displacement in reservoir engineering is intended as a mechanism of a fluid displacement that fills the porous medium by another fluid. In this waterflooding the displaced fluid is oil, while the displacing fluid is water.

In the laboratory oil recovery resulting from the displacement of oil by water injection is determined as a function of pore volumes of water injected and water cut. The resulting data is a graphic display of the expected performance of the reservoir rock in the area where oil is swept by water.

## III. METHODOLOGY

Methodology in this study consists of a number of interrelated procedures that are all conducted in the laboratory step by step to meet the requirements of doing waterflooding susceptibility in enhanced oil recovery from an a depleted oil reservoir. These procedures include the basic properties of reservoir rocks, relative permeability, wettability, water-rock compatibility, and the critical flow velocity.

To represent the reservoir rock as a subject for water injection rock samples were taken from conventional core samples resulting from coring in the Well X, XYZ Field, East Java at a depth interval of 825 - 830 meters (Table 1). The samples supplied by the company are sandstones in a cylindrical shape with a size of 10 inches in diameter. In addition, the formation water and injection water are also required to be used for displacement fluid in the waterflooding test. The formation water was also provided by the company, while the injection water was made synthetically based on the water that was taken from the field.

### A. Work Procedures

Waterflooding working procedure in the laboratory is described as follows.

### Core preparation and water injection

1. Prior to core flooding, first to be performed is core sample preparation and then injection of the core with water until 100% water saturation.

### Steps of Sample Preparation:

- Plugging core samples.

  Core samples are drilled in the form of cylinder plug with a diameter of 1.5 inches, one plug every foot of the core samples received from the field.
- Cleaning the samples

  Core plug samples are then cleaned using toluene soxhlet extractor so that the hydrocarbon content in the samples dissolved into toluene. Then they were washed using methanol to dissolve the salts from water formation.
- Drying the samples

  Samples are then dried in an oven with a temperature of about 80°C, after that they are conditioned in ambient conditions using a desiccator.

- Next, the rock samples are measured for their porosity and permeability.
- The samples are then injected with formation water to reach 100% water saturation.

2. Water saturates cores 100% are then injected with oil until the irreducible water saturation (Swir) condition has been reached.
3. Measuring the effective permeability to oil in the core at Swir condition (ko at Swir).
4. Measuring the waterflood using cores as step 3).

Cores at Swir condition are injected with formation water, then the fluid that displaced out of the cores is monitored until the water cut reached 99.96%.

5. When Sor conditions have been achieved, the next stage is the measurement of effective permeability to water in both direction of flow (kw at Sor).

The results of waterflooding analysis provides information about the behavior of water injection into the reservoir rock that still contains remaining oil saturation. The behavior of the reservoir that contains water injection is indicated by the increase in oil recovery (decrease Sor) as a function of water cut.

**B. Petrographic and Scanning Electron Microscopic Analysis**

For petrographic analysis of rocks, a slice of rock is mounted on a glass slide and then thinned in such a way so that rock can be penetrated by polarized light under microscope. In general, a thin section of rock should be at least 3 microns thick. Observation using a polarization microscope equipped with objective lens that can enlarge the object up to 100 times and ocular lens that can also enlarge the object up to 10 times. Visualization of minerals that can be seen from this polarization microscope is in the mode of a two-dimensional image. The study of Petrographic Analysis uses a Polarization Axio Imager Microscope A.2.

To get a picture of the texture of the rock and its relationship with the pores in the rocks in detail, a Scanning Electron Microscopy (SEM) was used to supplement the results of petrographic analysis.

By using SEM the textures of rock can be viewed in detail and clearly resulting from the magnification of SEM which can reach up to 20,000 times its original size. Figure 3 shows kaolinites, the

**Table 1**
**Basic parameter data**

| Sample Number | Depth (m) | Horizontal Permeability (mD) | Porosity (%) | Grain Density gr/cc |
|---|---|---|---|---|
| 1 | 825.20 | 16.00 | 20.26 | 2.65 |
| 1B | 825.20 | 52.05 | 21.84 | 2.64 |
| 4 | 826.21 | 76.00 | 23.20 | 2.66 |
| 4A | 826.21 | 34.54 | 23.02 | 2.66 |
| 4B | 826.25 | 110.30 | 25.78 | 2.64 |
| 4C | 826.25 | 118.90 | 25.44 | 2.65 |
| 6 | 826.76 | 33.00 | 22.70 | 2.65 |
| 6B | 826.76 | 43.30 | 24.90 | 2.66 |
| 9A | 827.88 | 41.29 | 22.97 | 2.65 |
| 9B | 827.92 | 2.27 | 14.88 | 2.64 |
| 10 | 828.10 | 62.55 | 23.16 | 2.65 |
| 11 | 828.46 | 139.00 | 28.53 | 2.66 |
| 1 A | 828.50 | 32.03 | 24.77 | 2.66 |
| 11B | 828.50 | 27.95 | 21.25 | 2.65 |
| 11C | 828.54 | 124.50 | 26.97 | 2.66 |

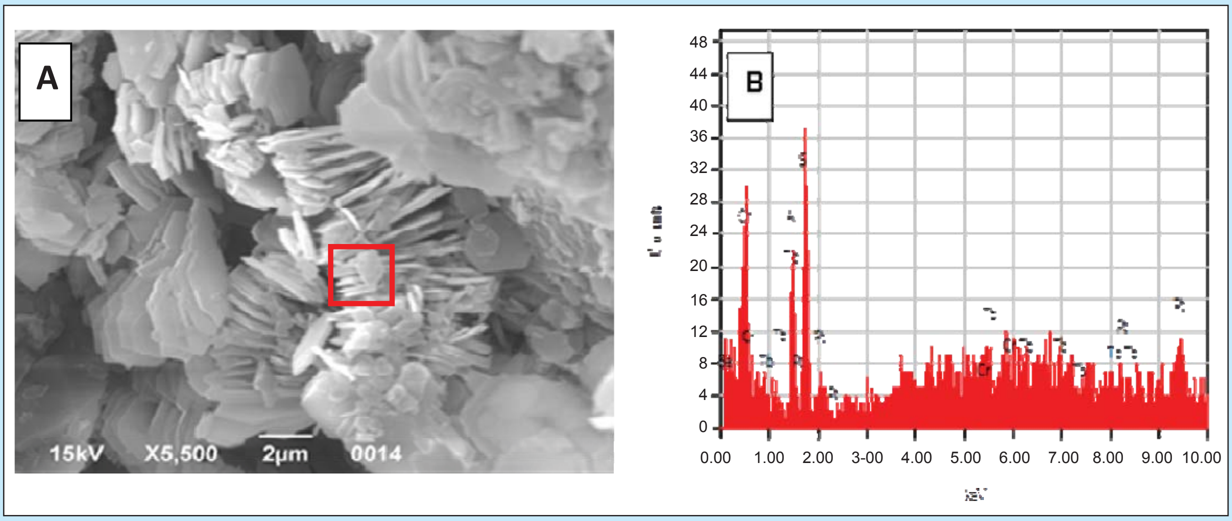


**Figure 3**
**Figure showing kaolinite mineral analysis from SEM (Figure 3A) and from EDX (Figgure 3B) deposited in a pore throat with a diameter larger than 75 µm. A Square at Figure 3A shows a spot location of EDX analysis.**

common clay minerals, which are easily found in sandstones of Ngrayong Fomation. From the SEM photomicrograph, kaolinites show a typical shape which resembles a book-like structure that filled the pore throats of the rock.

## IV. RESULTS OF LABORATORY DISCUSSION

### A. Analysis of Injection Water and Formation Water

Injection water for this study was obtained from the original water of The XYZ Field, while the formation water was made synthetically as shown in Table 2. This synthetic formation water is commonly called synthetic brine.

**Injection Water Design**

Based on the injection water analysis, all the water taken from water collector stations (Sub-Station, SP-1 and SPU-X stations) contains various components such as bacteria, crude oil, oxygen and scale that may cause problems in the system of oil production.

To avoid or reduce the problems during waterflooding especially the occurence of formation damage, injection water was designed by adding a number of chemical components (Table 3) comprising Corrosion Inhibitor Prolab, Reverse Demulsifier Prolab Crude Oil, Oxygen Scavanger Prolab, Bioxida Prolab, and Scale Inhibitor Prolab in such a way as to prevent the formation of scale, corrosion and plug that will lead to a decrease in permeability and damage to production equipment.

### B. Wettability

Wettability can be defined as the ability of a fluid phase to preferentially wet a solid surface in the presence of a second immiscible phase Wettability refers to the interaction between fluid and solid phases. In this laboratory test wettability was analysed using Amott’s method. The method combines two spontaneous imbibition measurements and two forced displacement measurements. This test defines two different indices, the Amott water index (WWI) and the Amott oil index (OWI) expressed in the following equation:

$$WWI = \frac{imbibed\ oil\ volume}{(imbibed\ oil\ volume\ + oil\ volume\ displaced\ by\ water)}$$

$$OWI = \frac{imbibed\ water\ volume}{(imbibed\ water\ volume\ + water\ volume\ displaced\ by\ oil)}$$

The results of wettability index calculation of the tests are presented in Table 4.

### C. Relative Permeability

The relative permeability is the ratio of effective permeability of the reservoir fluid contents in comparison to the absolute permeability (ka). In the case of the reservoir rock consisting of water and

Table 2
Water analysis

| No | Component analysis | Unit | Injection water | | |
|---|---|---|---|---|---|
| | | | Sub Station | SP-1 | SPU-X |
| 1 | Sodium, $Na^+$ (calc) | mg/L | 7787.70 | 3377.70 | 5586.50 |
| 2 | Calcium, $Ca^{++}$ | mg/L | 11.000 | 17.00 | 22.00 |
| 3 | Magnesium, $Mg^{++}$ | mg/L | 0.00 | 0.00 | 0.00 |
| 4 | Iron. $Fe^{++}$ (total) | mg/L | 0.00 | 0.00 | 0.00 |
| 5 | Barium, $Ba^{++}$ | mg/L | 0.00 | 0.00 | 0.00 |
| 6 | Chloride, $C1^-$ | mg/L | 10295.00 | 3408.00 | 6816.00 |
| 7 | Bicarbonate, $HCO_3^-$ | mg/L | 2708.40 | 2757.20 | 2366.00 |
| 8 | Sulfate, CO3- | mg/L | 0.00 | 0.00 | 0.00 |
| 9 | Carbonate | mg/L | 264.00 | 192.00 | 390.00 |
| 10 | Hydroxide | mg/L | 0.00 | 0.00 | 0.00 |
| 11 | Spec. Gravity @ 60/60°F | $^0$API | 1.0150 | 1.0083 | 1.0126 |
| 12 | pH @ 77°F | - | 7.86 | 7.60 | 7.59 |
| 13 | Salinity | mg/L | 19257.00 | 7787.70 | 13553.00 |
| 14 | Hydrogen Sulfide | mg/L | 0.00 | 0.00 | 0.00 |
| 15 | Hardness | mg/L | 27.50 | 42.50 | 55.00 |
| 16 | TDS(total dissolved solids) | mg/L | 183.00 | 98.00 | 125.00 |
| 17 | Resifitivity @125°F | Ohm-m | 0.2046 | 0.4656 | 0.2815 |

Table 3
The proposed chemical components as additive materials for the injection water

| No. | Name of Chemical Components | Purpose |
|---|---|---|
| 1 | Corrosion Inhibitor Prolab | Avoiding corrosion |
| 2 | Reverse demulsifier Prolab | Reducing the crude oil content in the injection water |
| 3 | Oxygen Scavanger Prolab | Reducing the oxygen content in avoiding the formation of corrosing |
| 4 | Bioxida Prolab is intended | Avoiding the growth of becteria |
| 5 | Scale Inhibitor Prolab | Avoid plugging |

oil, relative permeability of water (krw) is kw/ka, and relative permeability of oil (kro) is ko/ka. In addition, kw and ko are the effective permeability of water and oil respectively. Results of the relative permeability calculation are presented in Table 5.

$$Recovery\ Factor\ (RF) = \frac{Initial\ oil\ saturation - residual\ oil\ saturation}{Initial\ oil\ saturation}\ x\ 100\%$$

**D. Water-Rock Compatibility**

Water rock compatibility was done on 4 rock samples (4A, 4C, 9A, and 9B) following the two steps of the laboratory tests. The first step is injection using formation water and the second is injection using injection water. Firstly, injection was done by injecting formation water by as much as 5%PV. In this condition liquid permeability was measured. Formation water was then continued to be gradually injected until it reached 100%PV. In this condition again the liquid permeability was measured. In the next step the injection was continued using injection water following the same steps of formation water injection.

For samples 4A and 9A (Table 6) injection water used in the test is water without chemicals, while for samples 4C and 9B chemicals were added to the water (see additional chemical in Table 3).

### E. Critical Flow Speed (Critical Velocity)

From the plot between permeability/initial permeability with interstitial velocity (flow rate) it is clear that the water permeability starts to decrease at a flow rate of injection of 8.1322 cc/min (37.6 ft/day) and flow rate (interstitial velocity) of above

**Table 4**
**Wettability Index Calculation (Amott Method)**

| Sample Number | Depth (metres) | Permeability (%) | Porosity (%) | Wettability Index | |
|---|---|---|---|---|---|
| | | | | OWI | WWI |
| 1B | 825.20 | 52.0 | 21.84 | 0.0000 | 0.6981 |
| 4B | 826.25 | 110.30 | 25.78 | 0.0833 | 0.4793 |
| 6B | 826.76 | 43.30 | 24.90 | 0.0811 | 0.5256 |
| 11C | 828.54 | 124.50 | 26.97 | 0.1489 | 0.4737 |

*Notes: OWI = Oil Wet Index, OWI = 0 shows strongly water wet (equal to WWI = 1)*
*WWI= Water Wet Index, OWI = 1 shows strongly oil wet (equal to WWI= 0)*

**Table 5**
**Summary Data of Oil-water Relative Permeability**

***FIELD : XYZ***
***WELL : X***

| *Sample Number* | *Permeability (mD)* | | | *Porosoty (%)* | *Irreducible Water (% PV)* | *Initial Oil Saturation (% PV)* | *Resdidual Oil Saturation (% PV)* | *Oil Recovery (% PV)* | *Recovery Factor (%)* |
|---|---|---|---|---|---|---|---|---|---|
| | *To ($K_a$)* | *To Oil* ($K_{ro}$) at Irreducible water* | *To Water* ($k_{rw}$) at Residual Oil Saturation* | O | $S_{wir}$ | $S_{oi}$ (100-Swir) | $S_{or}$ | ($S_{or}$ - $S_{or}$) | RF |
| 11 | 139.20 | 77.75 | 5.9498 (8.4979**) | 28.257 | 26.280 | 73.520 | 29.109 | 44.411 | 60.407 |
| 4 | 75.85 | 28.31 | 3.5081 (4.9302**) | 23.202 | 27.995 | 72.005 | 28.133 | 43.872 | 60.929 |
| 6 | 33.41 | 5.05 | 0.3083 (0.4454**) | 22.697 | 28.494 | 71.506 | 36.631 | 34.875 | 48.772 |
| 1 | 15.97 | 31.15 | 0.1926 (0.2163**) | 20.256 | 29.808 | 70.192 | 38.095 | 32.097 | 45.727 |

*Notes:*
* *Relative to Air Permeability*
** *Measured in reversed direction to flow*

0.0133 cm/sec. The point where permeability is in the top position is referred to as the critical point (Sinclair and Duguid, 1990). Permeability of water will start to decline after the flow rate exceeds that point changing the flow from laminar into turbulent.

In order to prevent fine particles or minerals flowing to the wellbore which will cause blockage of neck pores (pore throat), the flow rate of injection at the waterflood laboratory trial should be maintained below the critical point of 0.0133 cm/sec.

**Table 6**
**Water Rock Compatibility**

| Sample Number | Formation Water | | % K reduction | Injection Water | | | | % K Reduction | Total % K Redoction | Ka (mD) | Kw/Ka ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | No chemical | | Added with chemical | | | | | |
| | $K_{w1}$ (mD) | $K_{w2}$ (mD) | | $K_{w1}$ (mD) | $K_{w2}$ (mD) | $K_{w1}$ (mD) | $K_{w2}$ (mD) | | | | |
| 4A | 12.12 | 5.24 | 56.73 | 7.58 | 4.59 | | | 39.39 | 62.12 | 34.54 | 0.35 |
| 9A | 27.58 | 11.66 | 57.72 | 18.87 | 10.23 | | | 45.76 | 62.90 | 41.29 | 0.67 |
| 4C | 50.00 | 19.16 | 61.68 | | | 29.43 | 13.88 | 52.84 | 72.74 | 118.9 | 0.42 |
| 9B | 1.33 | 0.86 | 34.91 | | | 1.06 | 0.71 | 33.53 | 46.78 | 2.27 | 0.58 |

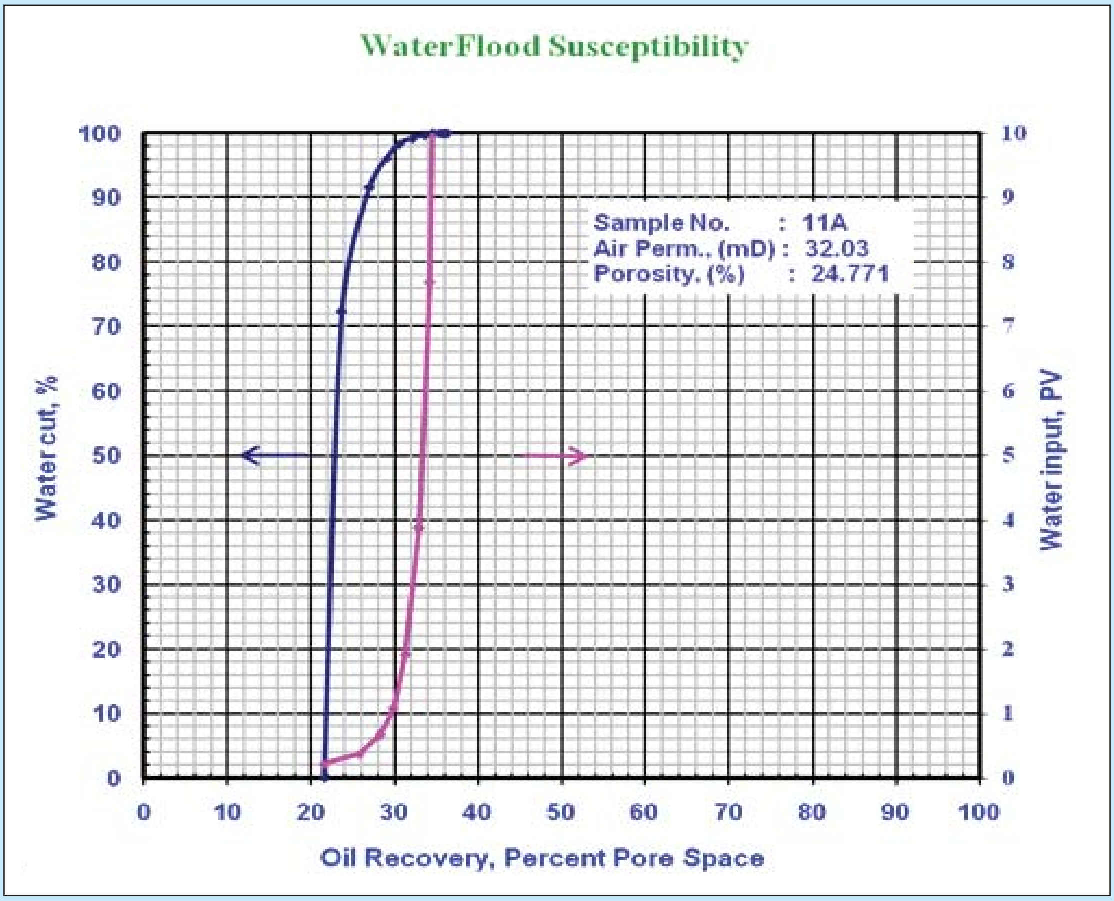


**Figure 4**
**Waterflood susceptibility graph for sample no. 11A.**

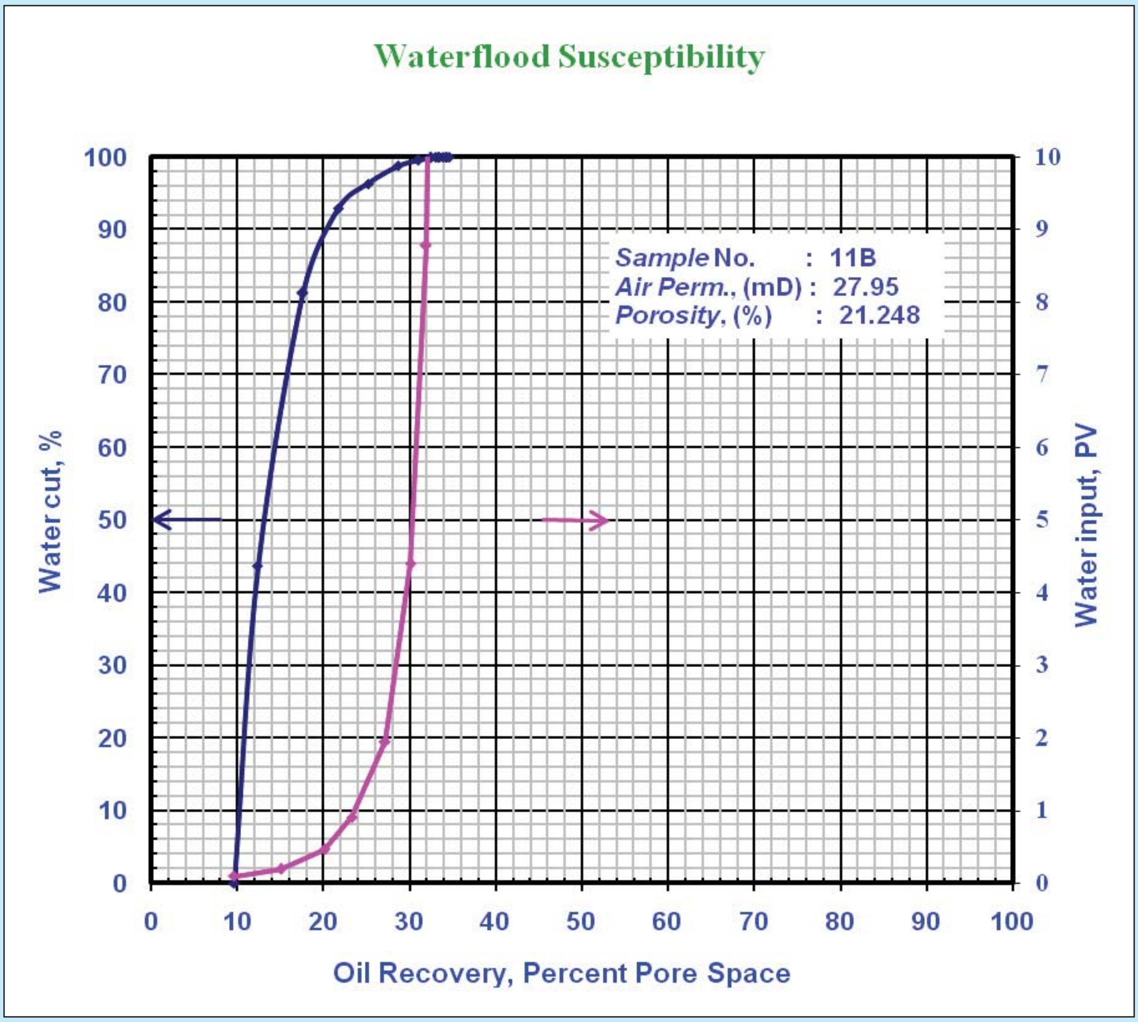


**Figure 5**
**Waterflood Susceptibility Graph for sample no. 11B.**

### F. Waterflood Susceptibility (WFS)

From the WFS test using core sample numbers 11A (Table 7) and 11B (Table 8) primary oil recovery was obtained as much as 35.63% PV for sample 11A (Figure 4), while for sample 11B the primary recovery amounted to 33.33%PV (Figure5). After getting primary oil recovery, the continued injection of the sample 11A by using water without any additional chemicals increased oil recovery becomes 36.40% PV (Table 7 and Figure 6). There is an increase of 0.77% PV oil.

Furthermore, for sample no. 11B was done using the injection of injection water added with chemicals, resulted in improved oil recovery being 34.65% PV, which is an increase of oil by 1.31%PV (Table 8 and Figure 7).

Table 9 shows that sample number 11B which has a smaller permeability value (27.95 mD) compared to that of number 11A with a higher permeability (32.03 mD) gave a higher enhancement oil recovery (1.31% PV) compared to that of sample number 11A where the increase is only as much as 0.77% PV. This experiment shows that injection water with additives gained greater increased oil recovery than the injection water without additives.

## V. CONCLUSION

The conclusions of this study are:

Analysis of the critical velocity (crtitical velocity) is done to avoid non-Darcy flow obtained yield was 0.0133 cm/sec (37.6 ft / day) is set as the maximum speed of the flow for the water injection.

Table 7
WFS Sample No. 11A

| Water input, (pore volume) | Comulatine oil recovery, (%pore space) | Average oil recovery*, (%pare space) | Average water cut** (%) |
|---|---|---|---|
| | | Injection of formation water | |
| 0.2154 | 21.4584*** | 21.5484 | 0 |
| 0.3686 | 25.7811 | 23.6647 | 72.3618 |
| 0.6610 | 28.2438 | 27.0124 | 91.5789 |
| 1.0766 | 29.8599 | 29.0518 | 96.1111 |
| 1.9076 | 31.2451 | 30.5525 | 98.3330 |
| 3.8739 | 32.9382 | 32.0917 | 99.1389 |
| 7.7010 | 34.2465 | 33.5924 | 99.6581 |
| 15.3004 | 35.0931 | 34.6698 | 99.8886 |
| 22.9692 | 35.4779 | 35.2855 | 99.9498 |
| **38.4152** | **35.6318** | **35.5548** | **99.9900** |
| | | Start of water injected | |
| 69.2017 | 35.9396 | 35.7857 | 99.9900 |
| 99.9874 | 36.1705 | 36.0551 | 99.9925 |
| 161.5559 | 36.3244 | 36.2474 | 99.9975 |
| 238.5152 | 36.4014 | 36.3629 | 99.9990 |

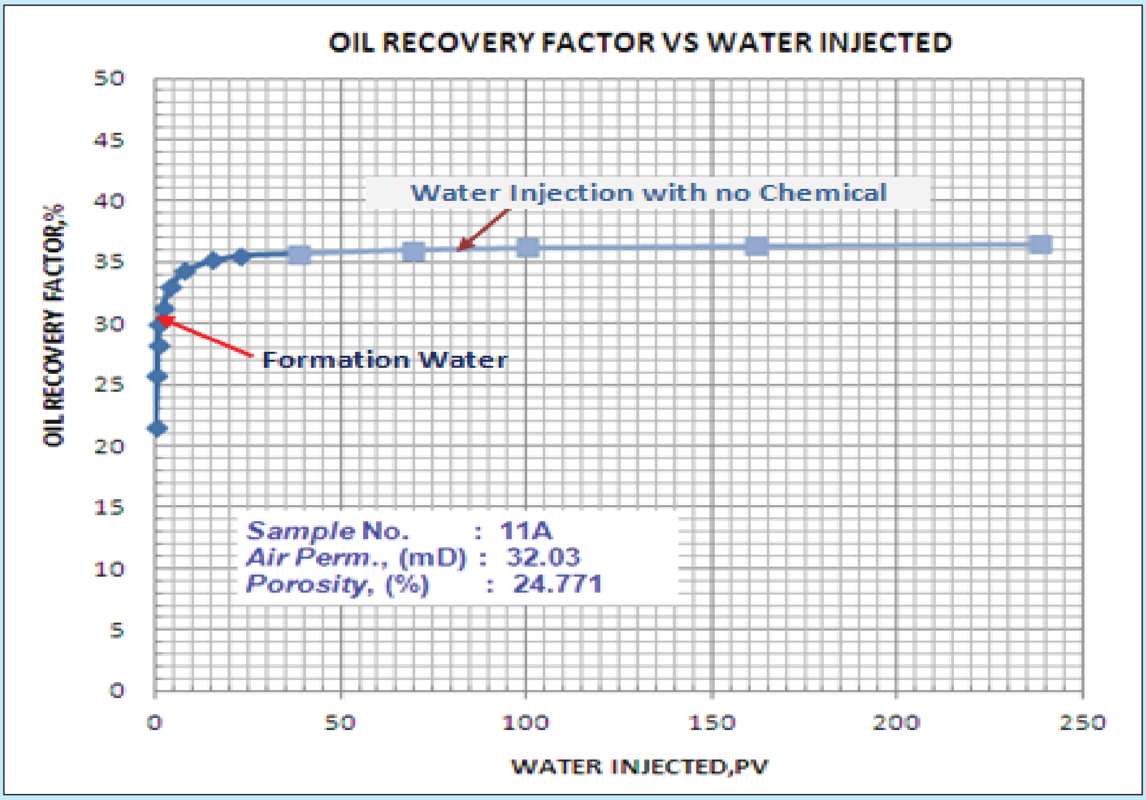


Figure 6
Oil Recovery Factor versus Water Injected for sample no. 11A.

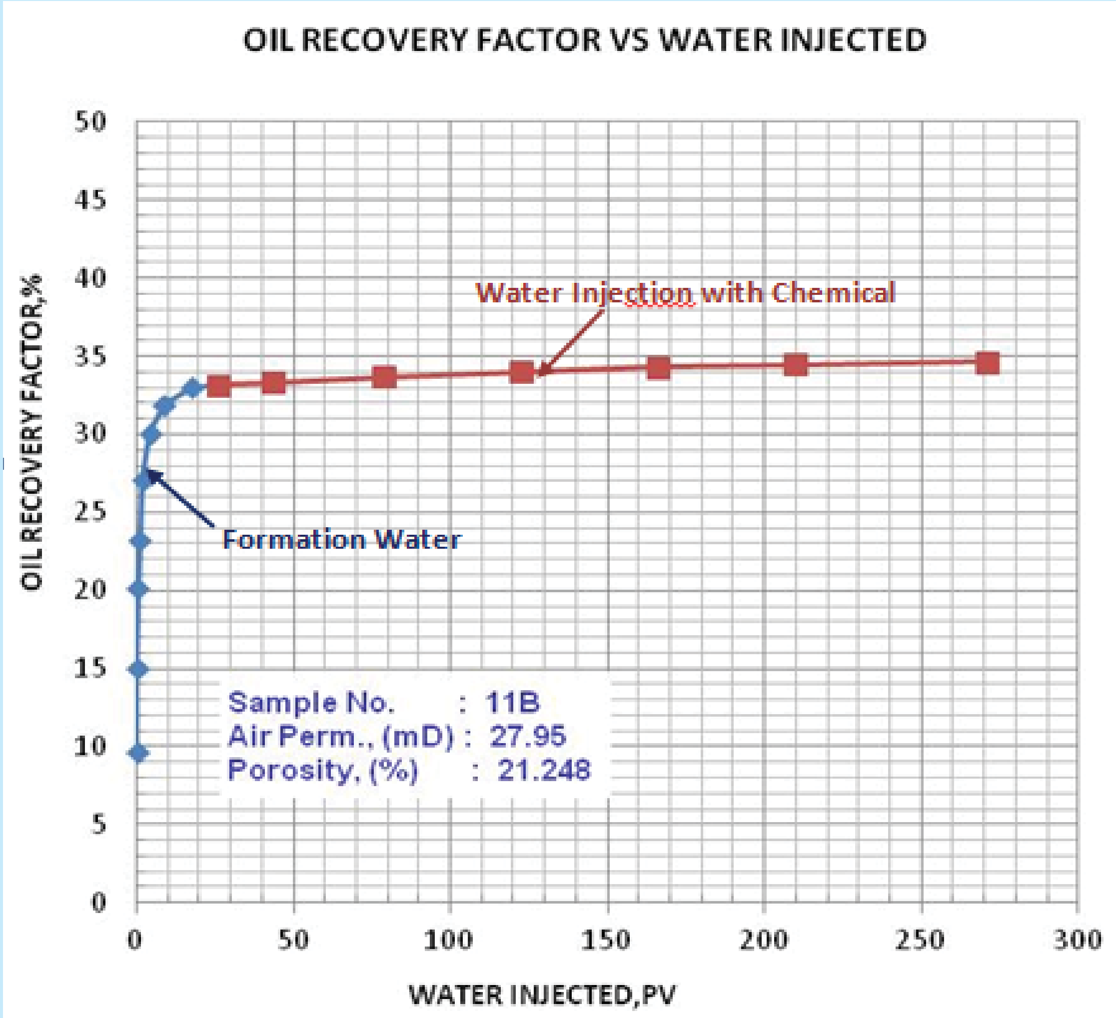


**Figure 7**
**Oil Recovery factor versus water injected for sample no. 11B.**

Based on waterflooding in laboratory experiments, the results of the oil recovery for sample 11A injected by formation water shows 35.63% PV (primary recovery). After formation water injection the sample was then displaced using injection water without additives, the oil recovery becomes 36.40% PV (secondary recovery). This recovery increased by 0.77% PV. For sample 11B that was injected using formation water, the oil recovery obtained was 33.33% PV (primary recovery). When the injection was continued using injection water added with chemicals, the oil recovery increased to 34.65% PV, or an increase of 1.31%.

From these test results it can be observed that the injection using injection water plus chemicals gives a result of increasing oil recovery greater than the use of injection water without additional chemicals.

## RECOMMENDATION

To carry out trials of waterflooding in the field it is recommended that the flow velocity of water injection not exceed the critical flow rate of 37.6 ft/day to avoid turbulency flow (non-Darcy flow) which can cause formation damage.

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**Table 8**
**WFS sample no. 11B**

| Water input, (pore volume) | Comulatine oil recovery, (%pore space) | Average oil recovery*, (%pare space) | Average water cut** (%) |
|---|---|---|---|
| | | **Injection of formation water** | |
| 0.062 | 9.6238*** | 9.6238 | 0 |
| 0.1925 | 15.0481 | 12.3360 | 43.6364 |
| 0.4628 | 20.1225 | 17.5853 | 81.2298 |
| 0.9046 | 23.2721 | 21.6973 | 92.8713 |
| 1.9519 | 30.0962 | 25.1969 | 96.3241 |
| 4.3928 | 31.9335 | 28.6089 | 98.7814 |
| 8.7786 | 32.9834 | 31.0149 | 99.5811 |
| 17.4398 | 33.1584 | 32.4584 | 99.8788 |
| 26.1448 | 33.1584 | 33.0709 | 99.9799 |
| **43.6737** | **33.3333** | **33.2458** | **99.9900** |
| | | **Start of water injected** | |
| 78.7237 | 33.6833 | 33.5083 | 99.9900 |
| 122.4410 | 34.0332 | 33.8583 | 99.9920 |
| 166.1573 | 34.2957 | 34.1645 | 99.9940 |
| 209.8762 | 34.4707 | 34.3832 | 99.9960 |
| 271.0862 | 34.6457 | 34.5582 | 99.9971 |

**Table 9**
**The experimental results of core samples injection with formation water and injection water**

| Sample Number | Porosity (%) | Permeability (mD) | Oil Recovery (%PV) | | | Enhancement Oil Recovery (%PV) |
|---|---|---|---|---|---|---|
| | | | Primary | Secondary | | |
| | | | Formation Water | Injection Water | | |
| | | | | No Chemicals | With Chemicals | |
| 11A | 24.77 | 32.63 | 35.63 | 36.40 | | 0.77 |
| 11B | 21.25 | 27.95 | 33.33 | | 34.56 | 1.31 |

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