Hydrothermal Alteration of Clay Minerals in EOR Injection Well

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Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Petroleum Engineering)

MAY 2013

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

Petroleum Engineering Programme

Universiti Teknologi PETRONAS

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BACHELOR OF ENGINEERING (Hons)

(PETROLEUM ENGINEERING)

Approved by,

____

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May 2013

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 have not been undertaken or done by unspecified sources or persons.

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SITI NABILAH BT ZAINUDDIN

ABSTRACT

In oil and gas industry, enhanced oil recovery (EOR) methods are very familiar and well known as a technique to increase the amount of crude that can be extracted from the reservoir. Then the thermal recovery or cyclic steam injection method is widely used for the heavy oil well which the heat will be distribute throughout the formation and the crude will be less viscous.

Even though this method can increase the crude production, it also creates another problem towards the clay minerals formation in the reservoir. As the steam injected into the well are high pH value and have low ionic strength, it will cause expansion and dispersion of water-sensitive clay and solubilization of silica and aluminum mineral. These conditions will reduce the formation permeability due to pore clogging.

From discussion and research with university's supervisor, author has been assigned to carry out the study of the effect of water molecule on the alteration of clay minerals and formation damage and to investigate the effect of injection rate on the alteration of clay minerals and formation damage in EOR project.

Few tests and experiment will be done throughout this year. The results and analysis will be recorded in the final report of the final year project.

ACKNOWLEDGMENT

Author would like to express her sincere gratitude and deep appreciation to the following people for their support, patience and guidance. Without them, this project wouldn't have been made possible. It is to them that author owing her gratitude.

- Dr Sonny Irawan and Mr Abdul Halim b Abdul for the continuous advice, guidance, constructive criticism and support to the author. Despite their heavy workload, they spared their precious time to discuss the project.
- Dr M Nur Fitri b Ismail and Mr Muhammad Aslam b Md Yusof, FYP Coordinators for their constant assistance, encouragement, guidance and excellent advice throughout this project.
- Lab technicians from various labs for the guidance rendered throughout this project period

Finally, above all, we would also like to thank author's family, friends, and Geoscience and Petroleum Engineering Department lecturers for their unwavering love, support and assistance throughout the project. Not to forget, special thanks also to Universiti Teknologi PETRONAS for providing her lab facilities to run the experiments and simulation.

TABLE OF CONTENTS

CERTIFICATION .... **i**

ABSTRACT .... **iii**

ACKNOWLEDGEMENT .... **iv**

TABLE OF CONTENTS .... **v**

LIST OF FIGURES .... **vii**

LIST OF TABLE .... **ix**

CHAPTER 1 - INTRODUCTION **1**

1.1 Background of Study 1

1.2 Problem Statement 2

1.3 Objective 3

1.4 Scope of Study 4

1.5 Limitation of Study 6

CHAPTER 2 – LITERATURE REVIEW AND THEORY 7

2.1 Enhanced Oil Recovery Well 7

2.2 Thermal Alteration 8

2.3 Thermal Recovery Method 10

2.4 Steam Quality 13

2.5 Berea Sandstone 15

2.6 Clay and its Properties 17

2.7 Clay Swelling Mechanisms..19

CHAPTER 3 – METHODOLOGY 21

3.1 Research Methodology 21

3.2 Key Milestones and Project Activities 22

3.3 Gantt Chart 23

3.4 Simulation Procedures 24

3.5 Experiment Procedures 27

CHAPTER 4 – RESULT AND DISCUSSION 32

4.1 Simulation (Eclipse300) Result 32

4.2 Experiment (Oedometer Test) Result 39

4.2 Simulation (Eclipse300) Discussion 45

4.2 Experiment (Oedometer Test) Discussion 46

CHAPTER 5 – CONCLUSION AND RECOMMENDATION 51

5.1 Conclusion 51

5.2 Recommendation for Future Works..51

REFERENCES 52

APPENDICES..54

LIST OF FIGURES

FIGURE 1 : EXAMPLE OF HYDROTHERMAL SYSTEM AND CIRCULATION. FROM "THE BLUE PLANET" BY BRIAN J. SKINNER (1995) 9
FIGURE 2: CYCLIC SYSTEM STIMULATION (HUFF AND PUFF OPERATION), (SLIDER, 1983) 12
FIGURE 3: CONDUCTION OF HEAT DURING HUFF AND PUFF SOAK PERIOD IN STRATIFIED RESERVOIR, (SLIDER, 1983) 12
FIGURE 4: EFFECT OF STEAM QUALITY ON OIL RECOVERY, (GOMAA, 1980) 14
FIGURE 5 : BEREA SANDSTONE (BEREA SANDSTONE™ PETROLEUM CORES, 2013) 15
FIGURE 6 : BEREA CORE SAMPLE 16
FIGURE 7: THE PRESENT OF CLAY MINERALS IN SEDIMENTARY ROCK AS MATRIX AND CEMENTING AGENT 18
FIGURE 8: CRYSTALLINE STRUCTURE OF SWELLING CLAYS. MZ+ REPRESENTS EXCHANGEABLE CATIONS (ZHIHONG (JOHN) ZHOU, 1997) 20
FIGURE 9: CORE SAMPLE BEFORE BEING CUT 28
FIGURE 10: CORE BEING CUT INTO 3CM IN HEIGHT 28
FIGURE 11: DISTURB SAMPLE BEING IMMERSE IN DISTILLED WATER 29
FIGURE 12: CONSOLIDATION APPARATUS 31
FIGURE 13: CONSOLIDATION SOFTWARE, DS 7 31
FIGURE 14: GRAPH OF OIL RECOVERY VS TIME FOR CLAY STONE AND SANDSTONE 32
FIGURE 15: GRAPH OF OIL RECOVERY FACTOR FOR INJECTION RATE OF 10000 (CLAY STONE) 33
FIGURE 16: GRAPH OF OIL RECOVERY FACTOR FOR INJECTION RATE OF 15000 (CLAY STONE) 34

FIGURE 17: GRAPH OF OIL RECOVERY FACTOR FOR INJECTION RATE OF 20000 (CLAY STONE) 35
FIGURE 18: GRAPH OF OIL RECOVERY FACTOR FOR INJECTION RATE OF 30000 (CLAY STONE) 36
FIGURE 19: GRAPH OF OIL RECOVERY FACTOR FOR INJECTION RATE OF 50000 (CLAY STONE) 37
FIGURE 20: COMBINATION OF ALL INJECTION RATES (CLAY STONE) 38
FIGURE 21: GRAPH OF VOID RATIO VS APPLIED PRESSURE 40
FIGURE 22: SETTLEMENT AND STRESS APPLIED VS TIME 48
FIGURE 23: SKETCH OF VOID RATIO VS LOG OF EFFECTIVE STRESS 49
FIGURE 24: MOVEMENT OF THE STRAIN 50

LIST OF TABLE

TABLE 1: RESERVOIR AND FLUID PROPERTIES USED 26
TABLE 2: SAMPLE PREPARATION DATA (WEIGHT).. 27
TABLE 3: SPECIMEN DETAILS BEFORE START THE TEST 39
TABLE 4: SPECIMEN DETAILS AFTER THE TEST 39
TABLE 5: OEDOMETER TEST RESULTS.. 40
TABLE 6: CHANGES PARAMETER IN THE SIMULATION 45

CHAPTER 1

INTRODUCTION

1.1 Background of study

The success of an EOR process depends on efficient delivery of injected fluid to the reservoir. In steam flooding, the majority of the energy is delivered through the latent heat of the two-phase steam, thus requiring that high quality steam be delivered to the reservoir sand face.

A simulation model will be developed to predict the hydrothermal alteration in EOR injection wells for different injection rate data sets. If the experimental model can be done, the inlet conditions of the flow are assumed to be homogeneous and dispersed.

Effluents from once-through steam generators often have pH values above 12 due to the use of high bicarbonate surface waters as feeds. Injection of these high pH and low ionic strength waters causes expansion and dispersion of water-sensitive clays and solubilization of silica and aluminum minerals. The hydroxide and carbonate ions in the effluents react with magnesium, calcium and other salts in formation waters to form precipitates.

Laboratory experiments showed that these alkaline boiler effluents irreversibly reduced the permeability of cores (by up to 70%), dispersed permeability of cores (by up to 70%), dispersed clays and solubilized quartz sands.

In the field, large quantities of amorphous precipitates containing magnesium, calcium and precipitates containing magnesium, calcium and aluminum as well as clays, micas and quartz grains were produced from two wells with low oil/steam ratios. The quartz grains showed substantial changes in surface morphology similar to those produced by quartz solubilization experiments in produced by quartz solubilization experiments in the laboratory.

To minimize reservoir damage, steam generator effluents with reduced pH and increased ionic strength are being injected at two field pilots.

1.2 Problem Statement

In oil and gas industry, thermal recovery methods used to reduce the viscosity of the in place oil. In the process, hot water or steam will be injected into the reservoir which further enhances the driving force. The main advantage of steam injection is that steam can be applied to wide variety of reservoir. But when it comes to clay formation, steam injection will produce hydrothermal reaction which can lower the potential production by reducing permeability and causing well bore damage.

The steam injection with high pH value which is very alkaline and low ionic strength has considerable potential for fluid-rock interaction, clay swelling and dispersion. Due to these interactions, there will be formation and well bore damage with subsequent impairment of oil production. Other problems occurred due to these interactions are solid invasion of well bore, degradation of gravel packs and plugging of surface equipment by producing solid.

Besides, steam injection which is difference composition of formation water can cause expansion and dispersion of water-sensitive clay. With high pH fluid, cleavage and slaking reactions of non-swelling clay will occur and it will reduce the formation permeability as water becomes more alkaline.

Injected steam of high temperature and high pH value also give problems to the oil production and reservoir formation. This situation can cause substantial dissolution and mobilization of reservoir minerals. Gravel packs also could be severely degraded with rapid loss of effectiveness due to this high temperature situation. When the gravel pack degraded, cavity will form then the formation will collapse and fail the function of liner and casing. As dissolved minerals migrate away from the well bore, the temperature will reduce causing the dissolved minerals re-precipitate in the pore space then reduction of permeability will occur.

1.3 Objectives

In this research, the author wants to understand and model the interactions between water molecules or thermal effect to predict the evolution of microstructure and properties of swelling clays.
This study embarks on the following objectives:

I. To investigate the effect of water molecules on the alteration of clay minerals;
II. To investigate the effect of injection rate on the alteration of clay minerals and formation damage in thermal EOR projects.

1.4 Scope of study

In this project, the scope of study will cover the application of hydrothermal alteration of clay minerals in EOR injection well. This study mostly involves simulation, experiment and few correlations. Below are the scopes of study that related and important for the finding:

I. Thermal Recovery Method

This method used is to reduce the viscosity of the in-place oil. High-temperature steam is injected into a reservoir to heat the oil. The oil expands, becomes less viscous and partially vaporizes, making it easier to move to the production wells. Steam flooding is generally used in heavy oil recovery to overcome the high viscosity that inhibits movement of the oil. In this project / research, steam injection or steam flooding or thermal effect will be used to determine the effect of hydrothermal towards the clay mineral in the formation.

II. Steam Properties

The properties of steam are very important because it will determine the reaction that can occur inside the formation. As steam used usually comes with high pH and low ionic strength, which can cause expansion and dispersion of water sensitive clays and solubilization of silica and aluminum mineral. These situations will reduce the permeability of the formation and causing well bore damage.

III. Heat Loss In Steam Injection

The heat losses in a system begin at the thermal unit or heat source, with subsequent heat losses occurring in the surface injection line, the injection wellhead, the wellbore and finally the formation itself and adjacent strata. In this research, author will investigate the amount the heat loss during the steam flooding and will study how to maintain the quality of the steam throughout the injection.

IV. Clay Formation Properties

The physical and chemical properties of the clay minerals will be identified and studied. The properties of the core sample from the real field will be studied such as its particle bonding, its cementing and the permeability inside the core sample. These properties can be relate to the reaction occurred during the hydrothermal alteration.

V. Clay Swelling Mechanism

Swelling clays in stone can generate damaging stresses during a wetting or a drying cycle, which leads to deterioration of building stones such as Portland Brownstone. There are two primary types of swelling identified for clays: short-range, ordered intracrystalline swelling and long-range, continuous osmotic swelling (Timothy Wangler, 2007). In oil and gas perspective, clay swelling became a major cause for formation damage in hydrocarbon reservoir. In enhanced oil recovery (EOR), the potential of formation damage is much greater because incompatible injection fluids often cause clay swelling (Zhihong (John) Zhou, 1997)

VI. One Dimensional Consolidation Theory

One Dimensional Consolidation Theory – Odometer Test, covers the determination of the magnitude and rate of the consolidation of a saturated or near saturated specimen of sol in form of a disc confined literally, subjected to vertical axial pressure and allowed to drain freely from the top and bottom surface. The method is concerned mainly with the primary consolidation phase but it can also be used to determine secondary compression characteristics. To relate with this project, the theory will be used to study the swelling of clay in the provided samples.

1.5 Limitation of Study

Although this project will be run with simulations and experiments to achieve its objectives, there will be limitation due to lack of time where it only have about 3 months to complete it. Besides, lack of equipment also affects the experimental works. Lastly, lack of field data (EOR Injection Well) also can be the limitation of the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Enhance Oil Recovery (EOR) Well

Enhanced oil recovery refers to the process of producing liquid hydrocarbons by methods other than the conventional use of reservoir energy and reservoir re-pressurizing schemes with gas or water. On the average, conventional production methods will produce from a reservoir about 30% of the initial oil in place. The remaining oil, nearly 70% of the initial resource, is a large and attractive target for enhanced oil recovery methods.

Enhanced Oil Recovery (EOR) injection wells are used to increase production and prolong the life of oil-producing fields. Secondary recovery is an EOR process commonly referred to as water–flooding. In this process, salt water that was co–produced with oil and gas is re-injected into the oil-producing formation to drive oil into pumping wells, resulting in the recovery of additional oil. Tertiary recovery is an EOR process that is used after secondary recovery methods become inefficient or uneconomical. Tertiary recovery methods include the injection of gas, water with special additives, and steam to maintain and extend oil production. These methods allow the maximum amount of the oil to be retrieved out of the subsurface. Approximately 60% of the salt water produced with oil and gas onshore in the United States is injected into EOR wells. (GWPC Official Web Page)

The relative location of the injection well depends on the geology of the reservoir, its type and the volume of hydrocarbon-bearing rock required to be swept in a time limited by economics. It is advantageous, where possible to make use of any favourable influence of gravity , for example in inclined reservoir, reservoir with a gas-cap or with an underlying aquifer. There are two types of injection well location: (Latil, 1980)

a) Central and peripheral flooding, in which the injectors are grouped together
b) Pattern flooding, in which the injectors are distributed amongst the production wells.

2.2 Thermal Alteration

A hydrothermal process is when are concentrated “by hot, aqueous solutions flowing through fractures and pore spaces in crustal rock” (Skinner, Porter, Botkin, 1995). Hydrothermal alteration in Glossary of Geology is defined as “These phase changes resulting from the interaction of hydrothermal stage fluid (‘hydrothermal solution’) with pre-existing solid phase such kaolonization of feldspars, etc and also used to cover changes in rocks brought about by the addition or removal of material through the medium of hydrothermal fluids, e.g silicification.

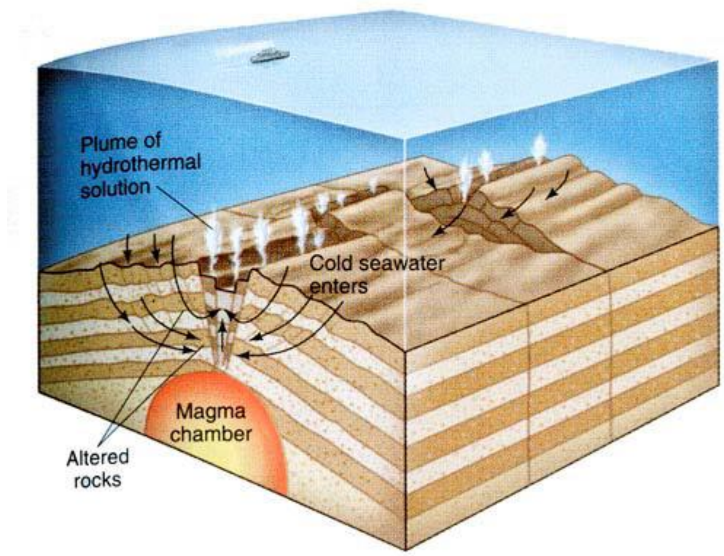


Figure 1 : Example of Hydrothermal system and circulation. From "The Blue Planet" by Brian J. Skinner (1995)

From the research paper of Hydrothermal Alteration by George M. Schwartz, he stated that the importance of hydrothermal alteration in relation to epigenetic ores was stated by Lindgren (56), as follow: “The study of changes and alteration which the rocks adjoining fissure have undergone is a subject of highest importance, for in this way a closer insight into genetics processes of the veins may be obtained.” Hydrothermal alteration is extremely varied and the kind of host rock obviously has large influence on the result. It is evident, however, that abundant changes in mineralogy and often in chemical composition can be made only by relatively large amount of solutions.

There are many factors involved with hydrothermal alteration. A few are, the type of rock being invaded by the aqueous solution, the composition of the aqueous solution, and the concentration of chemical potential of the fluid. Other important factors are temperature, pressure, and permeability. Some rocks are more easily invaded then others. For example, depending on the permeability of a rock, will figure into how much of the aqueous solution can actually get 4 into the pores and fractures. Permeability is the measure of how easily a solid allows a fluid to pass through. If a fluid can pass through easily then more of the rock will be altered and the other way around. Also remember, as the fluid moves through the rock it is collecting and re-depositing minerals. As it deposits these minerals they clog up the back trail allowing little or no other solution to pass through. This in turn will shorten the mineral vein.

Alteration textures range from weak alteration of only some of the minerals or matrix in the host rocks, producing a punky or earthy aspect to the overall rock, or to partiallyaltered phenocrysts. Such alteration may be difficult to distinguish from weathering in the field. Glassy rock matrix or fine-grained mesostasis can be particularly susceptible to alteration and may be massively silicified or replaced by chlorite or sericite as alteration intensity increases. At high alteration intensity, rocks may be pervasively altered, in which virtually all primary phases in the rock are altered to new hydrothermal minerals. In the extreme case of stringer zones immediately underlying massive sulfide deposits, it is not unusual to find massively altered rock that consists of quartz, chlorite, and chalcopyrite veins, with or without lesser amounts of pyrite, sericite, and carbonates. Stringer zone rocks may be unrecognizable in terms of original lithology. (Shanks, 2012)

2.3 Thermal Recovery Methods

Thermal enhance oil recovery process is a process that add heat to the reservoir to reduce oil viscosity and/or to vaporize the oil. These process will make the oil more mobile and be more effective driven to the producing well. Beside, it also provides a driving force to move the oil to the producing wells. (Speight, 2009)

Primary function of thermal recovery methods is to reduce the viscosity of the in place oil. There are two categories of thermal methods (Latil, 1980):

I. those in which the heat is produced at surface (hot fluid injection) : injected fluid carries the heat produced at their maximum temperature. It initially come into contact with the swept zone and there is consequently a significant heat loss.

II. those in which the heat is created in the formation (in-situ combustion) : injected fluid is one of the reactants involved in an exothermic reaction taking place in the reservoir where heat is only released exactly where it is required, i.e. where the oil is to be displaced.

The application of hot fluid injection is essentially dependent on its thermal efficiency and it depends on the heat losses both from the injection well bore to the surrounding formation and from the reservoir to the cap and base rocks.

For the cyclic steam injection method (Huff-and-puff operation), steam will be injected altenately into the well and producing heavy oil and steam condensate. This method includes three stages :

I. Stage 1 (Injection) : Measured amount of steam is introduced into the reservoir. In practice, steam is injected into formation at greater than fracturing pressure.

II. Stage 2 (Soaking) : The well will be shut in for a period of time (usually several days) to allow heat distribute uniformly to reduce the viscosity of the oil and also as a altenative to raise the reservoir temperature above the pour point of the oil.

III. Stage 3 (Production) : Less viscous and now-mobile oil will be produce from the production well or the same well.

This cyclic steam stimulation usually work best when there are thick pay zones which more than 10 meters with high porosity sands up (more than 30%). The minimum depth to apply this method is 1000 feet but it varies depending on the type and structure of the overlying formation. (Speight, 2009)

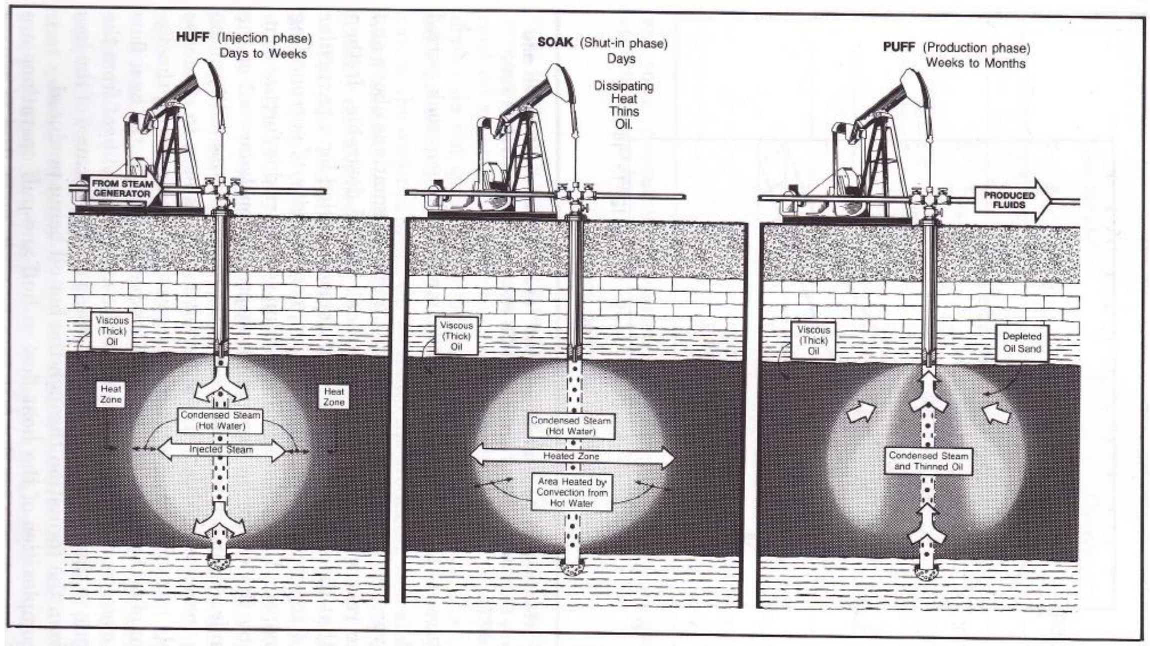


Figure 2: Cyclic System Stimulation (Huff and Puff Operation), (Slider, 1983)

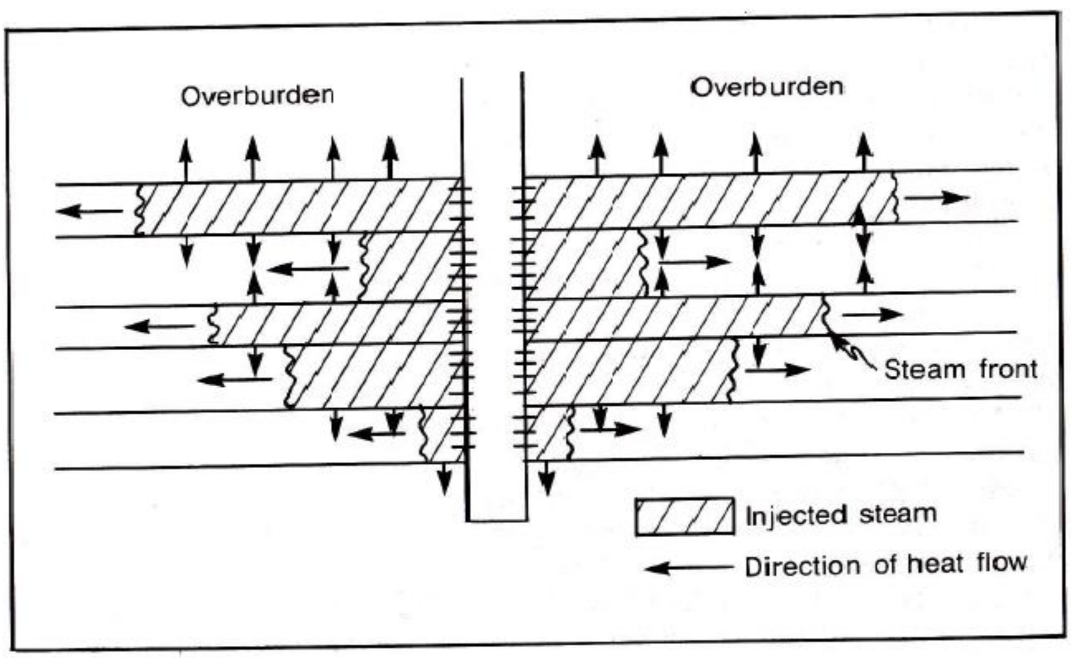


Figure 3: Conduction of heat during Huff and Puff soak period in stratified reservoir, (Slider, 1983)

According to McCorriston, A. Demby and C. Pease in their research paper of 'Study of Reservoir Damage Produced in Heavy Oil Formations Due to Steam Injection' : Injection of steam of lower salinity or different composition from the formation water can cause expansion of individual flakes, splitting of particles and deflocculation of clays from the quartz grains. Due to this situation, reservoir structure will destabilize and fine particle will migrate which can cause plugging of pore throat and will result the reduction of formation permeability. Regarding the quality of steam injection, they stated in their paper that it is common practice in steam stimulation to inject 8000 m^3 or more of 80% quality steam in each of several cycles per well. (Lois L. McCorriston, 1981)

From SPE 12499 (Steam Condensate: Formation Damage and Chemical Treatment for Injectivity Improvement) by Amaefule, P.C Padilla, F.G McCaferry and S.L Teal proposed fews remedial treatments to minimize the formation damage due to steam inejction (Amaefule, 1984):

I. by using calcium chloride solutions as preflush before steam injection to stabilize swelling clays and to protect them during subsequent fresh water contact.

II. By using hydroxy alumina as pretreatment before steam injection

III. By injecting saturated potassium chloride slug in pilot injection wells and continuous injection og KCl into generator feed water downstream of the softeners were effective in stabilizing clays and reducing condensate damage.

2.4 Steam Quality

Steam is the technical term for water vapor, the gaseous phase of water, which is formed when water boils. For the steam composition, it depends on the formation that will be injected. For example if steam injected in clay formation. As clay formation contain more calcium ions and magnesium ions, the steam composition should contain other ions that can replace the two ions (calcium and magnesium) in the clay formation. However, the steam quality is the propotion of the liquid (contain ions) and also vapor phase in the mixture. The steam quality can be defined as the ratio of mass in the vapor phase over total mass.

Normally, injection steam is raised in once-through steam generator and usually controlled to produce approximately 80% of quality steam. The normal practice is to inject the entire boiler effluent into the reservoir and this action lead to many problem toward the reservoir formation itself. For example, incremental of pH value due to fromation of sodium hydroxide that can cause substantial dissolution and mobilization of the reservoir minerals.

In a research (Gomaa, 1980), the author said that higher steam quality resulted in higher and faster oil recovery. Besides, author also said that the oil recovery increased with quality up to a point and then decreased, indicating an optimum steam quality in the range of 40%.

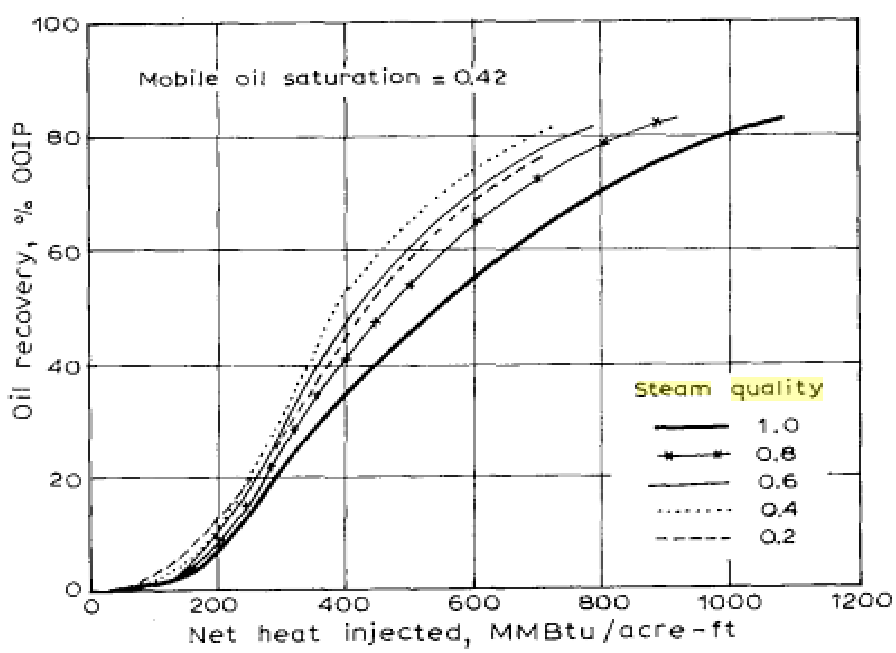


Figure 4: Effect of steam quality on oil recovery, (Gomaa, 1980)

According to another researcher (Chu, 1990), the author said that high-quality steam is favored for thin reservoirs whereas low-quality steam is more desirable for thick reservoirs. Based on Effects of Steam Quality and Injection Rate on Steamflood Performance research paper (Hong, 1994) for some steamflood situations, especially in massive, high-permeability reservoirs, gradual reduction of injection rate or quality may be desirable to optimize the use of steam after a period of injection at constant conditions and for situations involving layered, low-permeability (< 500 md) reservoirs, conversion of the steamflood to a water-alternating-steam process (WASP) may be desirable after steam breaks through to a producer.

2.5 Berea Sandstone (Core Sample)

Several quarried sandstone and carbonate rocks are used by the petroleum industry as standard porous media for laboratory experiments. Berea Sandstone is a sedimentary rock whose grains are predominantly sand-sized and are composed of quartz held together by silica. The relatively high porosity and permeability of Berea Sandstone makes it a good reservoir rock (Berea Sandstone™ Petroleum Cores, 2013).

Figure 5 : Berea Sandstone (Berea Sandstone™ Petroleum Cores, 2013)

Berea Sandstone also known as Berea Grit is Mississippian terrestrial sandstone. Outcrops of Berea sandstone in Ohio are found in filling previously cut channels in the underlying red Bedford and Chagrin shale. These channel-fill deposits consist of two distinct units. The lower unit of Berea Sandstone rests unconformably on the surface of the shale and is characterized by its reddish-orange color and high angle cross-bedding. This rock is coarser grained and more poorly-sorted than the Upper Berea sandstone unit. The Upper Berea sandstone unit is the rock most frequently used in core flood experiments. It is finer-grained, well-sorted sandstone with closely spaced planar bedding. Both of these Berea sandstones are quarried in Amherst, Ohio by Cleveland Quarries Company (P.L. Churcher, 1991).

The Berea Sandstone grains consist of predominantly quartz (85 to 90 %) and feldspar (3 to 6 %). The sand grains are cemented by quartz, dolomite (1 to 2 %), clays (6 to 8 %), and trace amounts of iron sulphides. Based on XRD analysis, the clay mineral assemblage consists of kaolinite (5 to 6 %), illite (1 %), and a trace of chlorite (P.L. Churcher, 1991). According to this research, the present of the clays can cause potential fine migration problem in the reservoir as the present of fresh water and high flow rate.

Figure 6 : Berea Core Sample

Core sample components :

a)	Silica	SiO_2	93.13%
b)	Alumina	AI_2O_3	3.86%
c)	Ferric Oxide	Fe_2O_3	0.11%
d)	Ferrous Oxide	FeO	0.54%
e)	Magnesium Oxide	MgO	0.25%
f)	Calcium Oxide	CaO	0.10%

Core Sample properties :

a)	Permeability	from 19mD to 2500mD
b)	Ambient Porosity	from 13% to 23%

**Source from* (Berea Sandstone™ Petroleum Cores, 2013)

2.6 Clay and its Properties

Clay is the common name for a number of fine-grained, earthy materials that become plastic when wet. Chemically, clays are hydrous aluminium silicates, usually containing minor amounts of impurities such as potassium, sodium, calcium, magnesium, or iron (UCL London's Global University, 2009 - 2013).

According to Justin P. Humphrey and Danial E Boyd in their book, clay minerals are typically formed over long periods of time by the gradual chemical weathering of rocks, usually silicate-bearing, by low concentrations of carbonic acid and other diluted solvents (Boyd, 2011).

There are few properties of clay minerals:

a) Plasticity
b) Shrinkage under firing and air drying
c) Fineness of grains
d) Color after firing
e) Hardness
f) Cohesion
g) Capacity of the surface to take decoration

Individual clay particles are usually smaller than 0.004 mm and clay often form colloidal suspensions when immersed in water, but they clump and quickly settle in saline water. In addition, clays are easily moulded into a form that they retain when dry, and they become hard and lose their plasticity when subjected to heat.

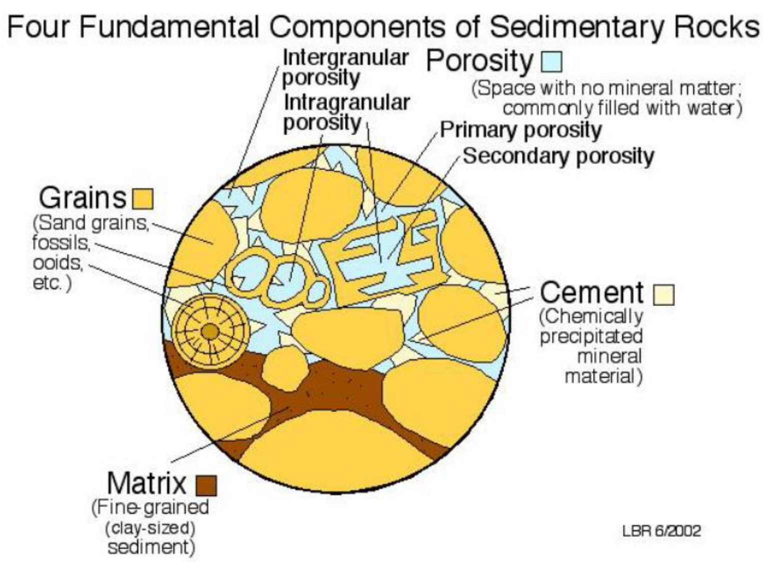


Figure 7: The present of clay minerals in sedimentary rock as matrix and cementing agent

2.7 Clay Swelling Mechanisms

Clay swelling has been identified as one of the major problem of formation damage in reservoir formation. For conventional oil production, clay related problem usually occur near the well region and they are related to the well operation such drilling, completion, work over and etc. According to a research regarding the clay swelling, enhanced oil recovery (EOR) have much greater potential of formation damage because injection fluids often cause clay swelling or fines migration and thus impair the formation permeability (Zhihong (John) Zhou, 1997). Besides, the reservoir formations which do not contain smectite also can have smectite-related formation damage due synthesizing of smectite clays through mineral or f1uid reactions during thermal recover.

To confirm this problem of clay swelling due to thermal recovery, core flooding experiment can be done. During the experiment, the reduction of permeability is considered as the effect of the formation damage. But, this situation cannot be totally depends on the clay swelling because formation damage also occur due to other mechanisms such fine migration or mineral growth.

X-ray diffraction (XRD) method is introduced to study the swelling of the clay. XRD method requires a small amount of sample but can quantify the effects of solution composition, clay composition, temperature and pressure on clay swelling. Clay swelling is a direct result of the (001) d-spacing increase and volume expansion when the exchangeable cations are hydrated in aqueous solution (Zhihong (John) Zhou, 1997).

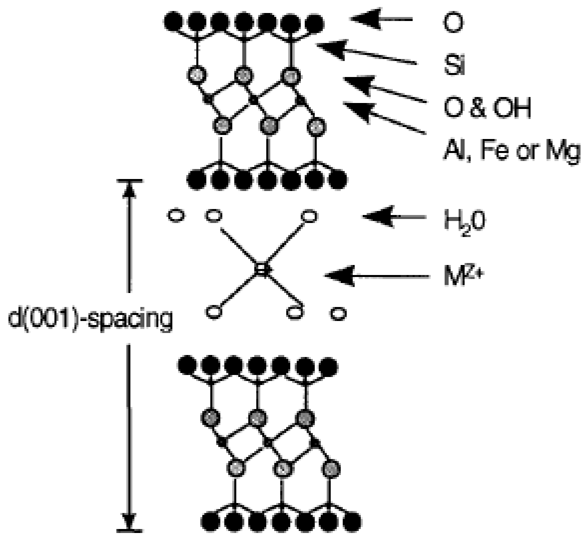


Figure 8: Crystalline structure of swelling clays. MZ+ represents exchangeable cations (Zhihong (John) Zhou, 1997)

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

Literature review and information gathering

All information involved being collected, obtained through article, book, journal paper and World Wide Web.

Understanding the Theoretical aspects

Regarding the water molecules reaction and thermal reaction on the clay minerals

Analyze the conceptual theories

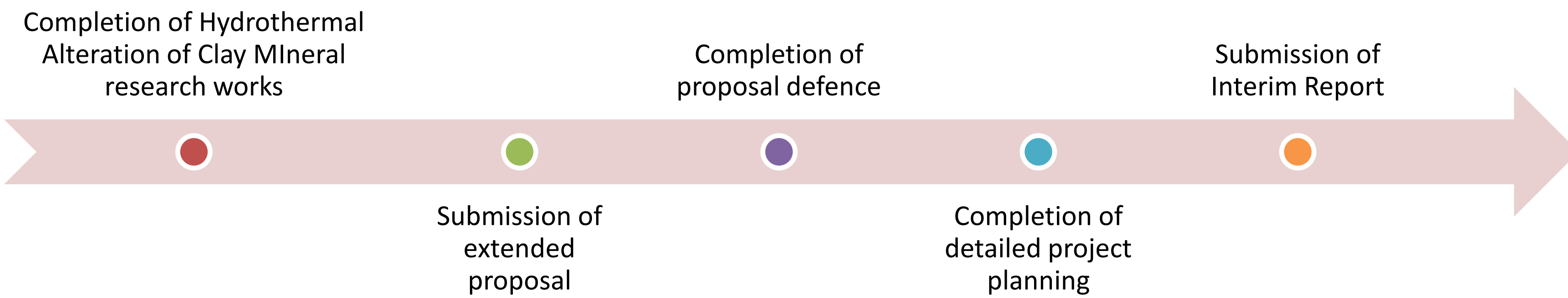
Several cases will be tested in which the steam properties will be varied by using eclipse software and one dimension consolidation test will be conducted to investigate the clay swelling due to interaction with water molecules.

Data Interpretation

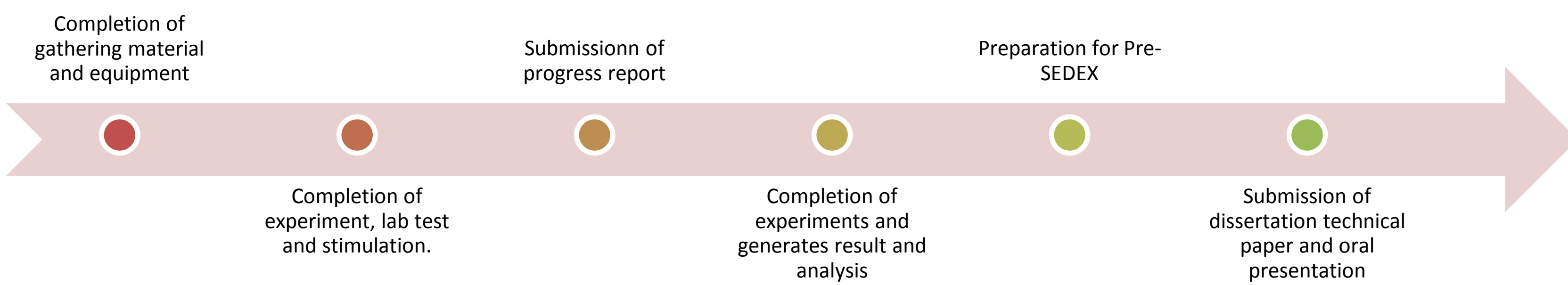
Data collected from the experiment and simulation will be interprets and conclusion will be draw.

3.2 Key Milestones and Project Activities

FYP 1



FYP 2



3.3 Gantt Chart

PROJECT ACTIVITIES	WEEKS																											
	Final Year Project 1														Final Year Project 2													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Topic Selection and Proposal																												
Preliminary Research Work																												
Submission of Extended Proposal																												
Identify material and equipment																												
Proposal Defense																												
Project Work Detailed Planning																												
Submission of Interim Draft Report																												
Submission of Interim Report																												
Gathering Materials																												
Conducting Experiments and Lab Tests																												
Submission of Progress Report																												
Result Analysis and Discussion																												
Pre-SEDEX Preparation																												
Submission of Draft Report																												
Submission of Dissertation *(soft bound)*																												
Submission of Technical paper																												
Oral presentation																												
Submission of Project Dissertation *(hard bound)*																												

The above Gantt chart shows the proposed activities for the project during FYP I and FYP II. Based on the Gantt chart, the project is feasible in the given time frame

3.4 Simulation Procedure (ECLIPSE 300)

Simulation Preparation:

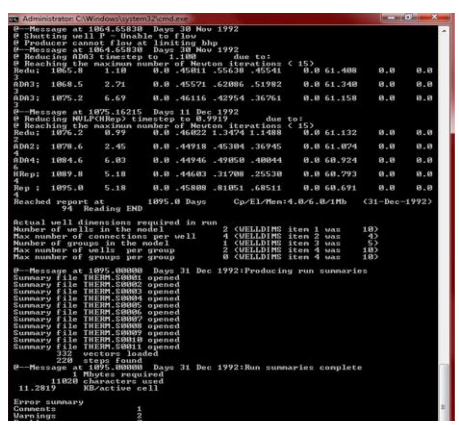
Collect all required data for the simulation such as Reservoir and Fluid Properties for heavy oil, PVT data and etc.

↓

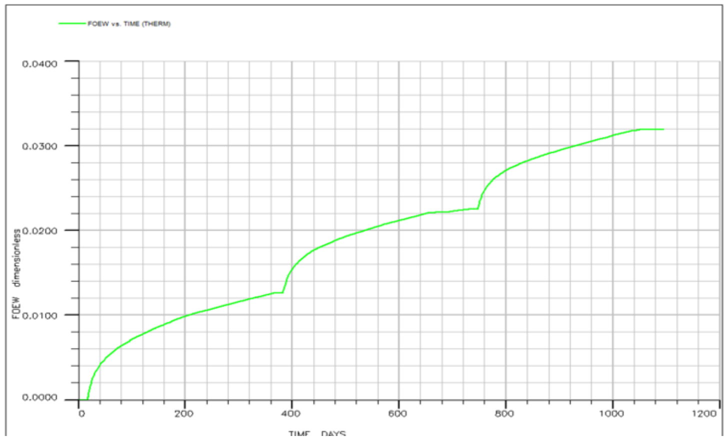
Convert all dataset into DATA file:

↓

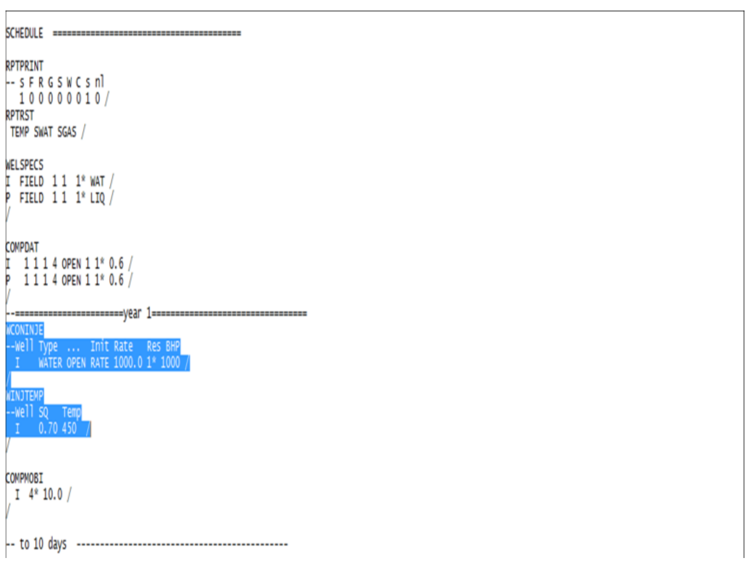
Run the DATA file by using ECLIPSE 300



View the result in the Simulation Launcher Office for the Recovery Factor (FOEW)



Repeat the procedure for different injection rate and steam quality required in SCHEDULE Section



```
SCHEDULE ========================================

RPTPRINT
-- s F R G S W C s nl
  1 0 0 0 0 0 0 1 0 /
RPTRST
 TEMP SWAT SGAS /

WELSPECS
I  FIELD  1 1  1* WAT /
P  FIELD  1 1  1* LIQ /
/

COMPDAT
I   1 1 1 4 OPEN 1 1* 0.6 /
P   1 1 1 4 OPEN 1 1* 0.6 /
/
--======================year 1================================
WCONINJE
--Well Type  ...  Init Rate   Res BHP
  I    WATER OPEN RATE 1000.0 1* 1000 /
/
WINJTEMP
--Well SQ   Temp
  I    0.70 450  /
/

COMPMOBI
  I  4* 10.0 /
/

-- to 10 days  ---------------------------------------------
```

Reservoir and fluid properties used in simulation (ECLIPSE 300):

Table 1: Reservoir and fluid properties used

Model grid	13 x 1 x 4
Initial pressure, psia	75
Initial reservoir temperature, ^{0}F	90
Porosity, %	30
Horizontal permeability, md	2000
Vertical permeability, md	1000
Oil viscosity, cp :	
at 75 ^{0}F	5780
at 500 ^{0}F	2.5
Compressibility :	
Water, psi^{-1}	3.0 x 10^{-6}
Oil, psi^{-1}	5.0 x 10^{-6}
Formation, psi^{-1}	5.0 x 10^{-4}
Formation heat capacity, Btu/(ft^3- ^{0}F)	35
Formation thermal conductivity, Btu/(D-ft- ^{0}F)	24.0

**Data source from* (K. Aziz, 1987)

3.5 Experiment Procedure (Clay Swelling Test)

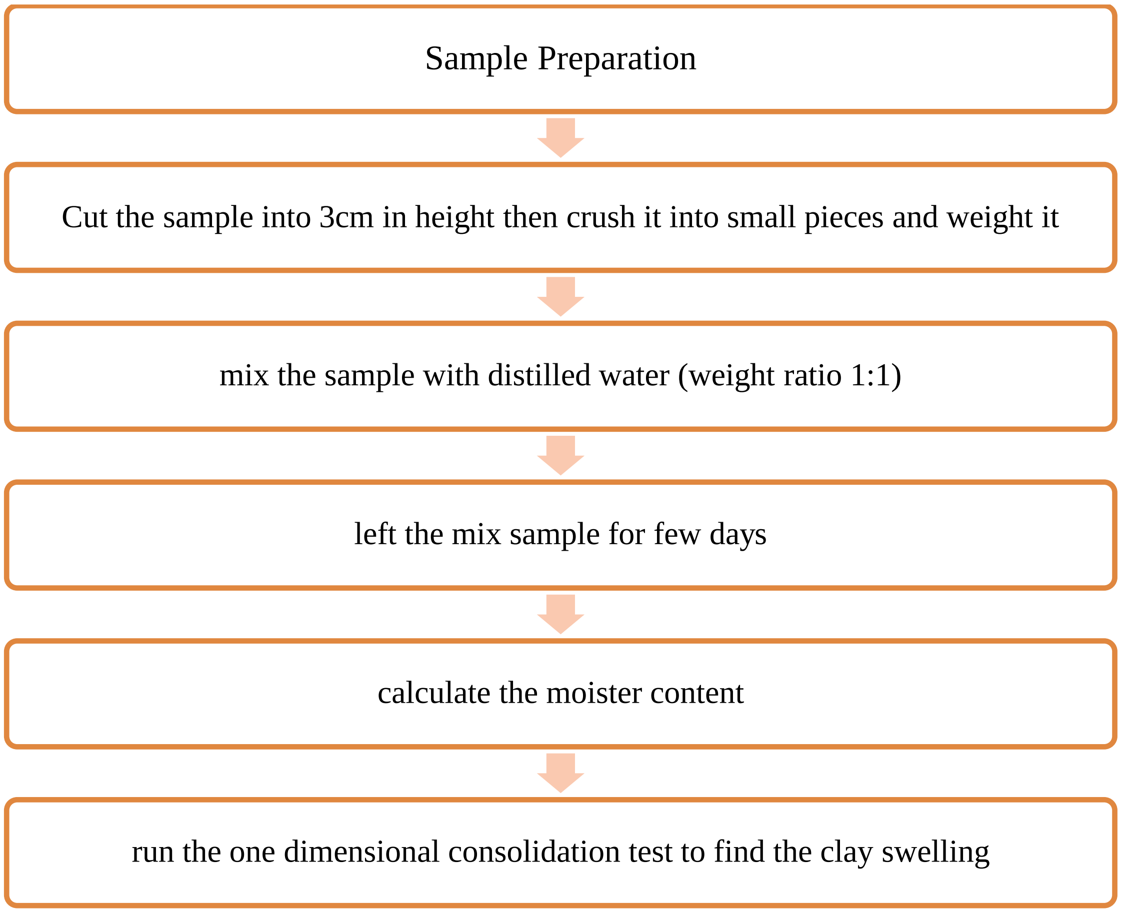


Table 2: Sample Preparation Data (Weight)

Sample		Weight of the sample, (g)	Weight of distilled water, (g)	Weight of mixture, (g)
Disturbed	A	78.79	78.82	159.76

Figure 9: Core Sample before being cut

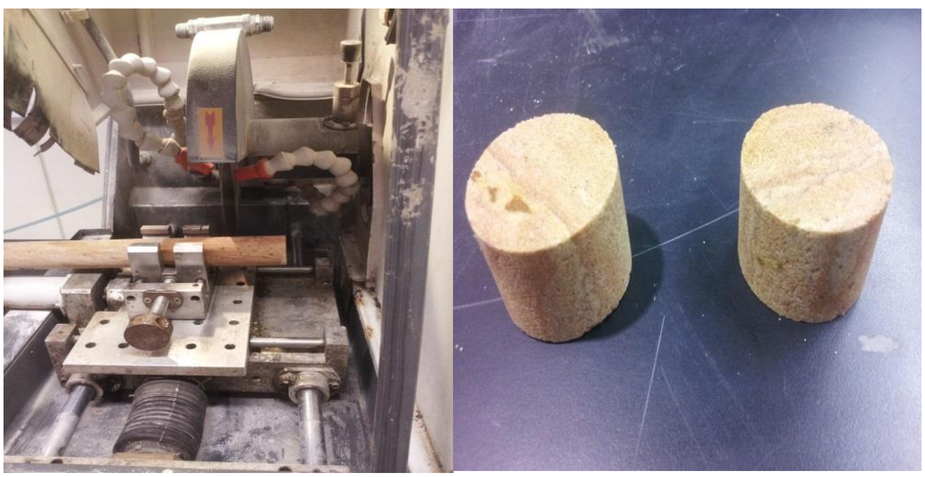


Figure 10: Core being cut into 3cm in height

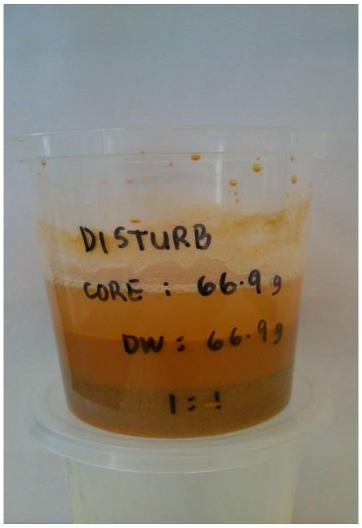


Figure 11: Disturb Sample being immerse in distilled water

One Dimensional Test / Odometer Test

A. Apparatus used

1. Consolidation apparatus
2. Balance readable to 0.1g
3. Consolidation Software, DS 7

B. Preparation of apparatus

1. Check the apparatus in complete order.
2. Check that the beam moves freely and that the weight hanger is fitted to the required lever ratio.
3. With the loading yoke in the vertical position, adjust the counterbalance weight as necessary so that the beam and hanger assembly is just in balance.
4. Wind up the beam support until touch the beam.

C. Trimming speciment into the ring

1. Place the ring on the flat glass plate and sample is tamped into the ring in two or three layer.
2. Keep the ring firmly in contact with the glass plate.
3. The speciment and faces are trimmed flat.

D. Assembly of consolidation cell

1. With the lower porous dics located centrally on the base of the cell, lower the consolidation ring and speciment centrally into the disc.
2. Fit the ring retainer an cell body around the ring so that it is securely held and tighten the fixing nuts progressively.
3. Attach the tranducer to the arm on the support post.
4. Add water at room temperatureto the cell without delay, so that the speciment an upper porous disc are completely submerged.

E. Addition of weight to hanger

1. Add weight carefully to the load hanger to give the required initial pressure. Weight should be placed on the hanger systematically. The main (lower) weight pan is inteded for the largest slotted weight and the upper one for the smaller slotted weight.
2. Place additional weight on the hanger to give the required pressure in between 24 hours. After loading sequence has been loaded, the weight will be unloaded according to unloading sequence.
3. The loading and unloading stages depend on the graph computed by the computer. When speciment considered to be fully loaded and consolidated, the increment/decrement of load can be added/taken off.

Figure 12: Consolidation Apparatus

Figure 13: Consolidation Software, DS 7

CHAPTER 4

RESULT AND DISCUSSION

4.1 Simulation Result (from ECLIPSE 300)

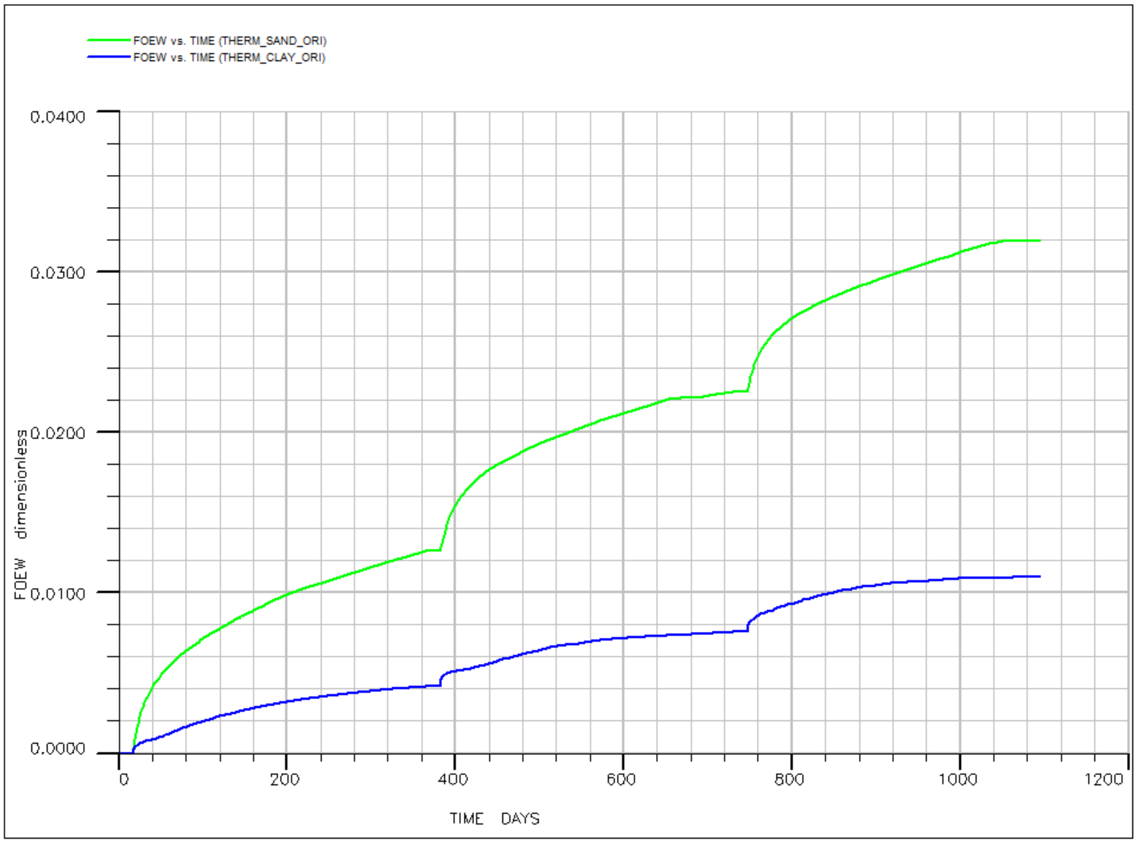


Figure 14: Graph of Oil Recovery vs Time for Clay stone and Sandstone

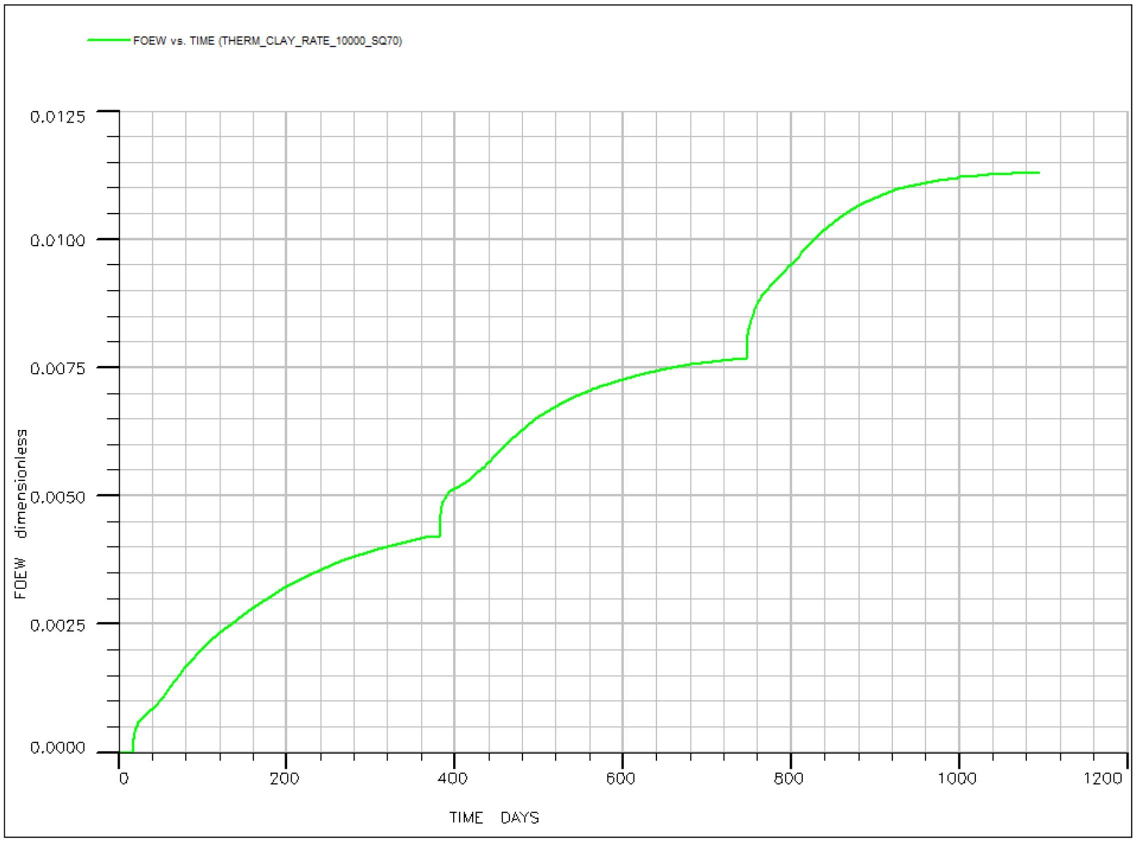


Figure 15: Graph of oil recovery factor for injection rate of 10000 (clay stone)

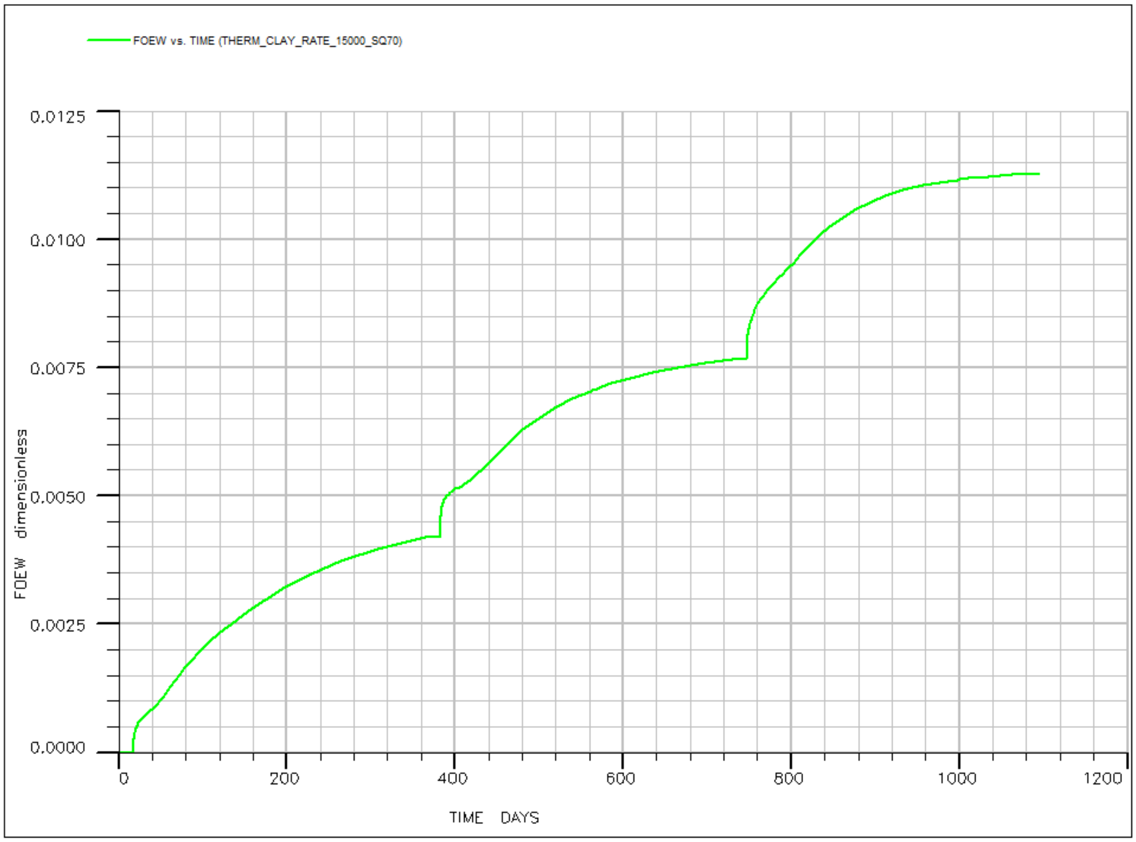


Figure 16: Graph of oil recovery factor for injection rate of 15000 (clay stone)

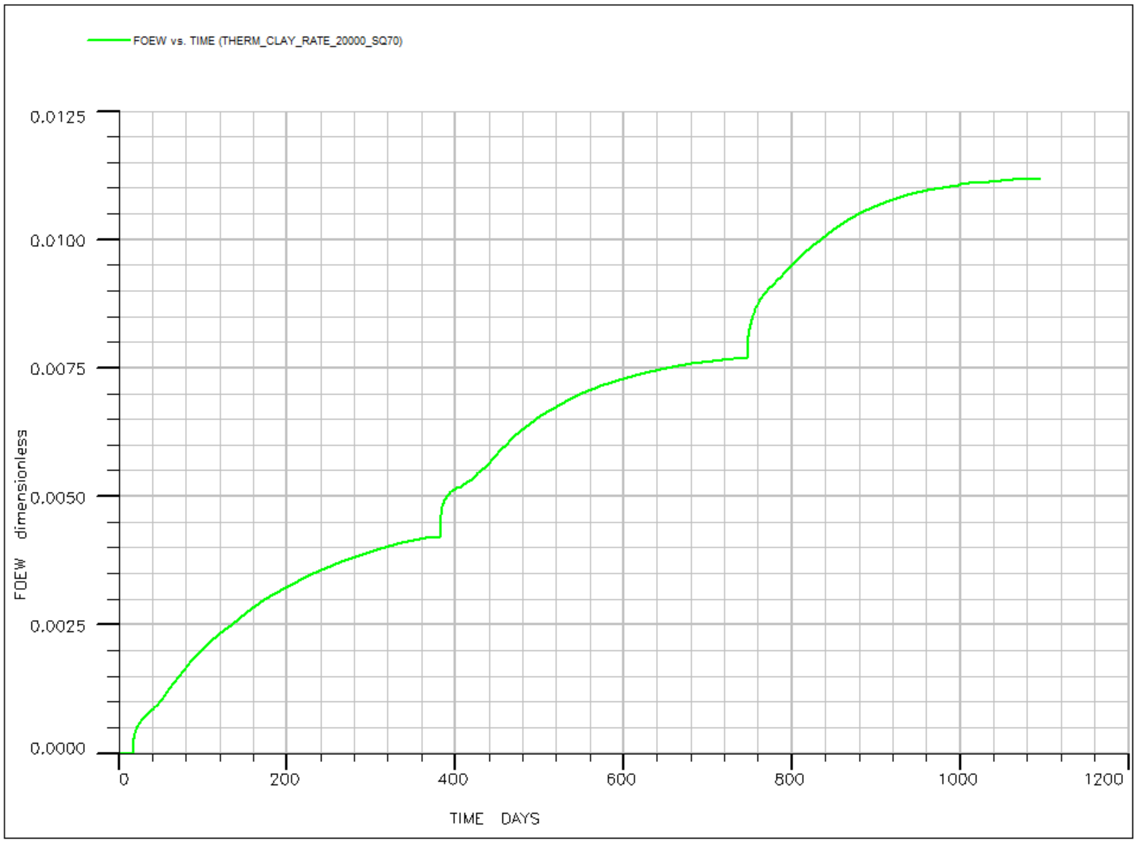


Figure 17: Graph of oil recovery factor for injection rate of 20000 (clay stone)

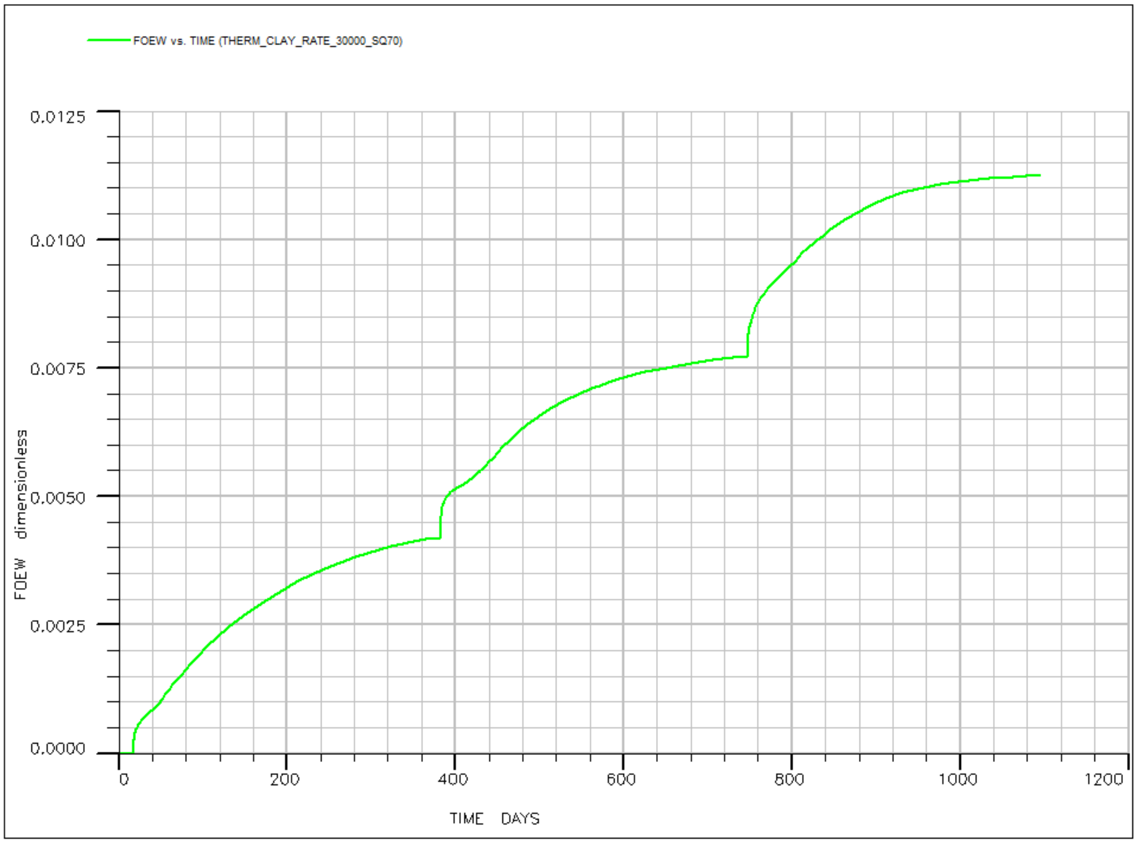


Figure 18: Graph of oil recovery factor for injection rate of 30000 (clay stone)

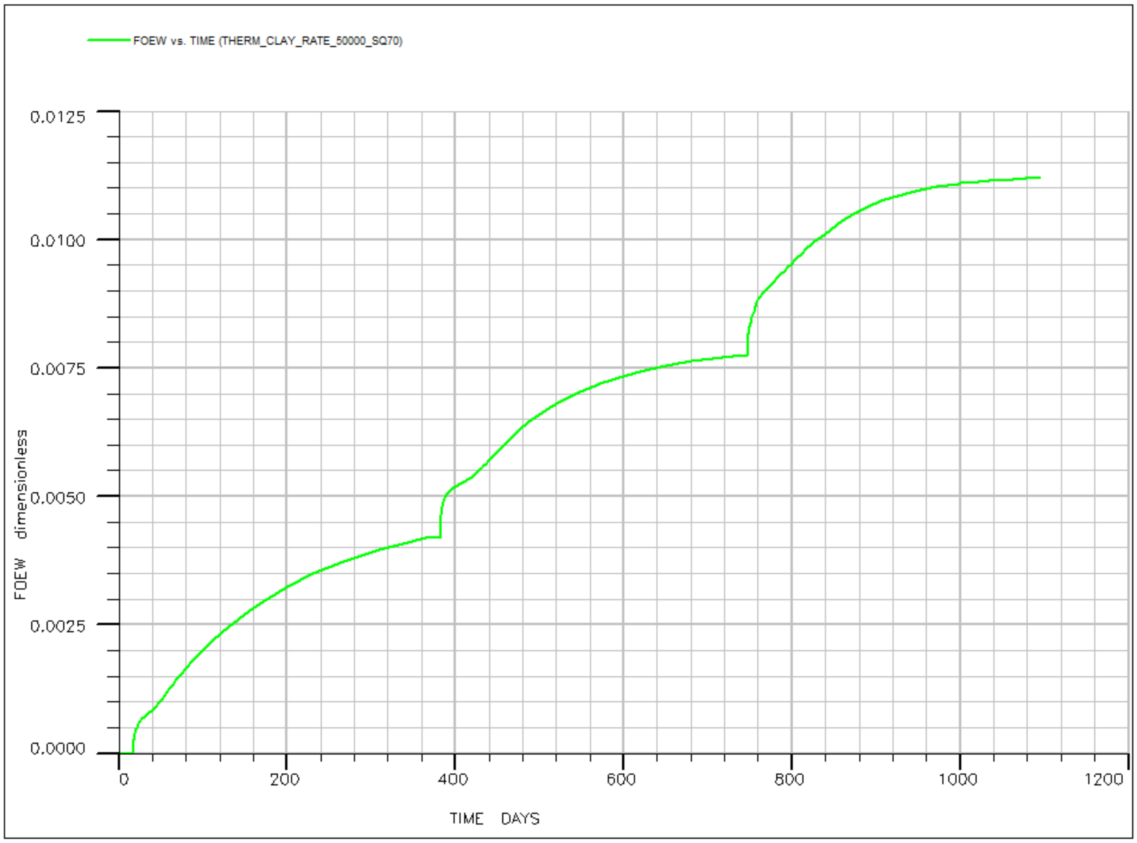


Figure 19: Graph of oil recovery factor for injection rate of 50000 (clay stone)

z

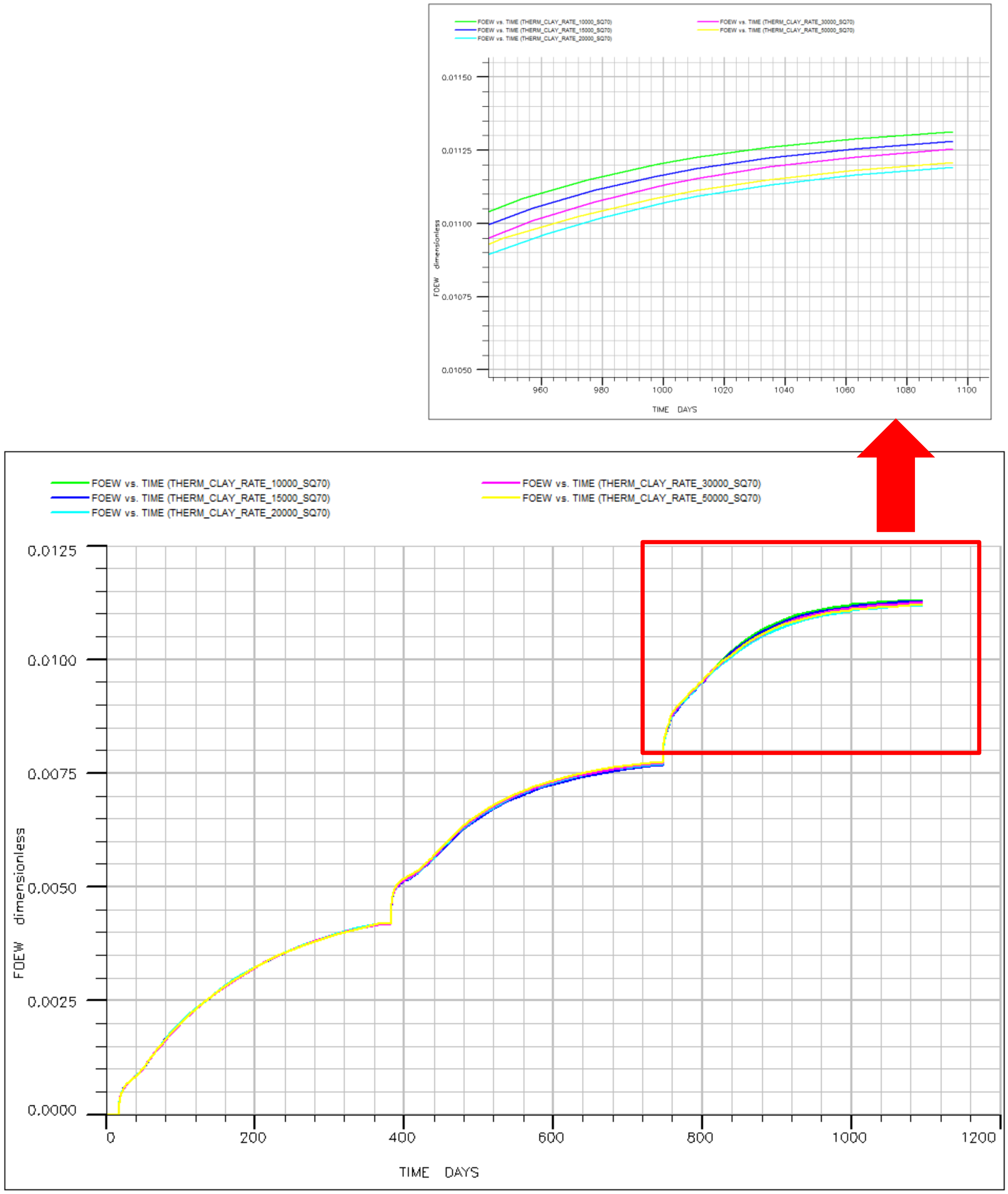


Figure 20: Combination of all injection rates (clay stone)

4.2 One Dimensional Consolidation Test Result

Sample A – Disturbed Sample (Depth: 365.76m – 457.2m)

Table 3: Specimen Details before start the test

Specimen Details :		Initial :
Diameter Ring	(mm)	49.58
Area Ring	(mm2)	1930.64
Length Ring	(mm)	19.65
Volume	(cm3)	37.94
Weight of ring	(g)	66.8
Weight of ring and specimen	(g)	141

Table 4: Specimen details after the test

After Test:		
Mass	(g)	74.2
Dry Mass	(g)	29.4
Moisture Content	%	11.8

Table 5: Oedometer Test Results

Pressure (Loading Stages)	Coefficient of Volume Compressibility (m_v)	Coefficient of Consolidation (c_v)
0.00		
50.0 kPa	0.53m^2/MN	303.89 m^2/Year
200.0 kPa	0.03m^2/MN	-11.59 m^2/Year
400.0 kPa	0.05m^2/MN	452.97 m^2/Year
800.0 kPa	-0.04m^2/MN	291.65 m^2/Year

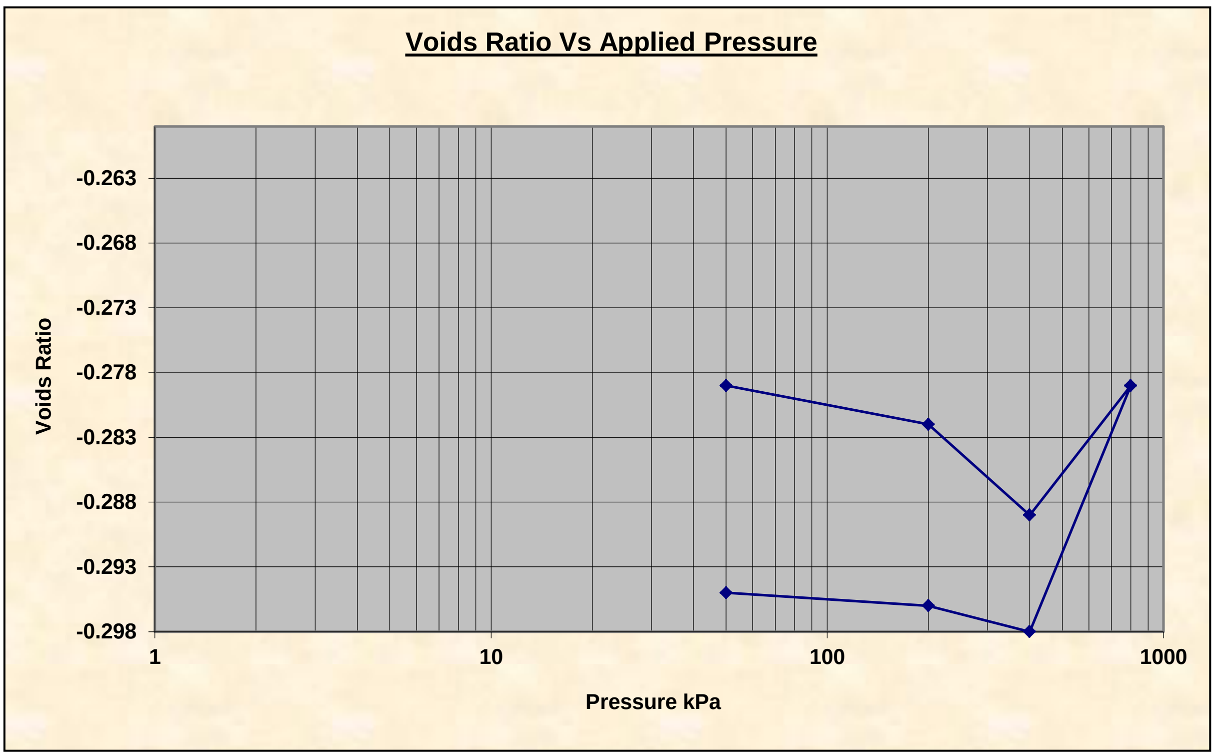


Figure 21: Graph of Void Ratio vs Applied Pressure

Ultimate settlement:

$$SSUL = \left[\frac{e_0 - e_f}{1 + e_0}\right] H$$

$$SSUL_{S1} = \left[\frac{0.278 - 0.293}{1 + 0.278}\right] 365.76$$

$$\boldsymbol{SSUL_{S1} = -4.29\ m}$$

$$SSUL_{S2} = \left[\frac{0.278 - 0.293}{1 + 0.278}\right] 457.2$$

$$\boldsymbol{SSUL_{S2} = -5.37\ m}$$

Constant Plastic Index:

$$CPI = \frac{\ln \frac{\Delta e\, H}{SSUL}}{\ln e_0}$$

$$CPI_{S1} = \frac{\ln \frac{(-0.015)(365.76)}{(-4.29)}}{\ln 0.278}$$

$$\boldsymbol{CPI_{S1} = -0.19}$$

$$CPI_{S2} = \frac{\ln \frac{(-0.015)(457.2)}{(-5.37)}}{\ln 0.278}$$

$$\boldsymbol{CPI_{S2} = -0.19}$$

Void Ratio Function:

$$F(e) = e_0^{CPI}$$

$$F(e) = 0.279^{-0.19}$$

$$\boldsymbol{F(e) = 1.27}$$

Stratum Index:

$$\alpha = ln\left[\frac{F(e)_{S1}}{F(e)_{S2}}\right]$$

$$\alpha = ln\left[\frac{1.27}{1.27}\right]$$

$$\alpha = 0$$

Strain (%):

$$\varepsilon = \frac{F(\mathrm{e}) - 1}{F(\mathrm{e})}\left[1 - \frac{1}{\alpha}\ [1 - \exp\ (-\alpha)\,]\right]$$

As α is equal to zero; the value of strain is only depends on $\frac{F(\mathrm{e})-1}{F(\mathrm{e})}$.

4.3 Simulation (Eclipse300) Discussion

Based on the first graph, there show that the recovery of the oil reduces as the formation is different. In the simulation, all the parameter for both situations is same except for the value of rock compressibility and value of thermal conductivity of rock and fluid.

Table 6: Changes Parameter in the simulation

Formation	Rock Compressibility, (psi^{-1})	Thermal Conductivity of rock and fluid, (Btu/ft./day/^{0}F)
Sandstone	5.00E-04	24
Clay Stone	2.90E-05	48.54

From the result also, we can see reduction of the recovery. This situation may occur due to formation damage during the steam injection. As stated in the literature review section, clay will swell when they interacts with water molecules and also the present of heat. This clay swelling may cause the formation damage then reduce the oil recovery. But formation damage also can happen due to others activities such completion, perforation and etc.

Figure 13, 14, 15, 16 and 17 shows the oil recovery factor in clay stone with injection rate of 10000, 15000, 20000, 30000 and 50000 stb/day. According to figure 18, injection rate of 10000 stb/day give the highest recovery factor. As the injection rate increase, the recovery factor starts to decrease. Even though the decrement of the recovery factor is small, in can give high impact toward the production and economy.

This decrement in recovery factor may due to the formation damage. As the injection rate increase, the formation starts to damage slowly and reduce the permeability inside the formation. As the permeability reduces, the oil has the restriction to flow towards the wellbore then it can reduce the production. As stated before, as in clay formation, the clay mineral will expand and block the flow then reduce the permeability.

According to the simulation result also, the optimum injection rate in the clay formation is 10000 stb/day as if the rate is increasing, the recovery start to decreasing.

4.4 Discussion for One Dimensional Consolidation Test / Oedometer Test

According to Table 4, the moisture content has been calculated using the direct method which is:

$$\theta = \frac{m_{\text{wet}} - m_{\text{dry}}}{\rho_w \cdot V_b}$$

Where:

m_{wet} and m_{dry} are the masses of the sample before and after drying in oven (g);

ρ_w density of water (g/cm^3);

V_b volume of the sample before drying

Moisture content is the quantity of water contained in a material and it is being used in a wide range of scientific and technical areas. This moisture content is expressed as a ratio, which can range from zero (completely dry) to the value of the materials' porosity at saturation. For this test, the moisture content of the sample is 11.6 percent. The moisture content depends largely on the porosity of a sample. As a sample has been compacted the result will be that the water content will decrease, as the inter-basal spacing between the pores will have been decreased.

As the experiment is completed, a graph of void ratio versus applied pressure was directly plotted from the consolidation software, DS7. There are two stages in the experiment which are loading and unloading stage.

During the loading stage, applied pressure is gradually increasing and it is directly transferred to the sample. Thus, the effective pressure at the top of the sample increases, whereby the solidosity and specific sample resistance increase as well. The effective pressure at the sample medium interface is equal to the applied pressure if the medium interface is negligible.

As in loading stage, primary consolidation occurs. It is defined as the reduction in volume of the sample mass by the application of a sustained load to the mass and due principally to a squeezing out of water from the void spaces of the mass accompanied by the load from the sample water to the solid sample. At this stage, the settlement of the sample is gradually reduced in volume of void upon loading. As in saturated sample (clay), the reduction of void volume occurs due to dissipation of excess pore-water pressure.

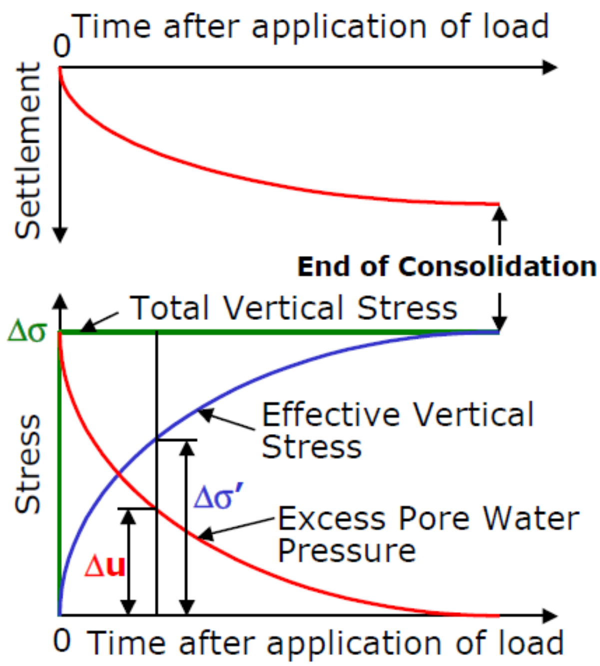


Figure 22: Settlement and stress applied vs time

The sample in this experiment is majority contain sand and minority contain clay. For sand consolidation, the permeability of the sand is high and drainage occurs almost instantaneously which is the settlement is immediately occurred. Sand is an elastic sample and consolidation processes cannot be isolated and the primary consolidation cannot corporate in the elastic parameters. The coarse grains of the sands (soils) do not undergo consolidation settlement due to relatively high hydraulic conductivity compare to clayey soils. Instead, coarse-grained sands (soils) undergo immediate settlement.

As the sample used in this experiment is majority contain sand, the result of the oedometer test is not really achievable. However, the concept is still the same. As the loading or stress applied increase, the void ratio will be decrease but the reduction is too small.

The completion of consolidation for the first increment under the vertical stress of 50 kPa, another 150 kPa of vertical stress is applied so that the vertical stress during the second increment is 200 kPa. For the third increment, another 200 kPa of vertical stress is applied and give the third increment to 400 kPa. The last vertical stress applied in the loading stage for the final settlement is 800 kPa.

During the consolidation test, a small amount of compression is occurred when the total pressure applied is less than the maximum overburden effective stress in the field to which the sand has been subjected in the past. However, when the total applied pressure on the specimen is greater than the maximum effective past pressure, the change in void ratio is much larger, as the void ratio (e) vertical stress (σ') relationship is particularly linear with a steeper slopes. This relationship is verified during the test by loading the specimen to exceed the maximum effective overburden pressure and the unloading it.

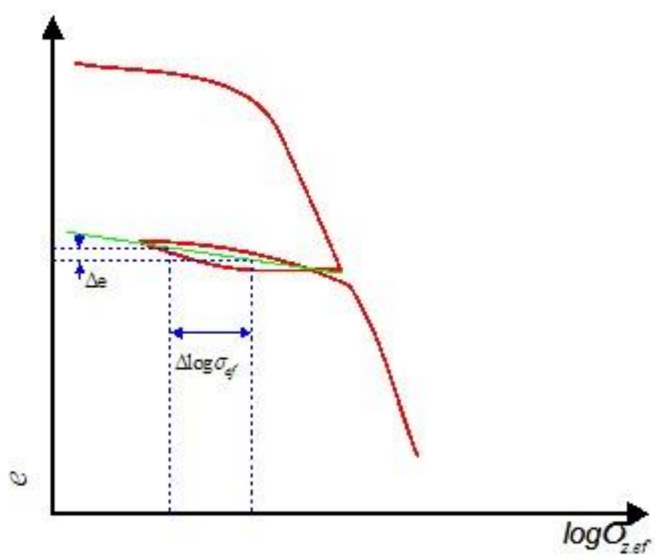


Figure 23: sketch of void ratio vs log of effective stress

The swelling point of the sample (sand) which is containing clay minerals can be interpreted from the graph of void ratio (e) versus vertical stress (σ') when the curve starts to rebound. Starting from that point, the properties of the sample start to be constant. Meaning that, when it is related to reservoir formation, during this time the rock and formation properties will fixed and there will have damage inside the formation. The damage will cause the reduction in permeability and can reduce the production.

For the calculation part, the value of strain is only depends on $\frac{F(e)-1}{F(e)}$ as the stratum index is equal to zero. The value of strain will describe the relative displacement between particles in formation. As the strain value is positive, it will move to the right side while if the value is negative, it will move to the left side. Meaning that, as the stratum move to the right side, it can consider as swelling or the wellbore area become larger while as the stratum move to the left side, it can consider as shrinking or the wellbore area become smaller. It is good if the strain value is positive as in can larger the wellbore area but if the strain value is negative, it can cause collapse to the wellbore.

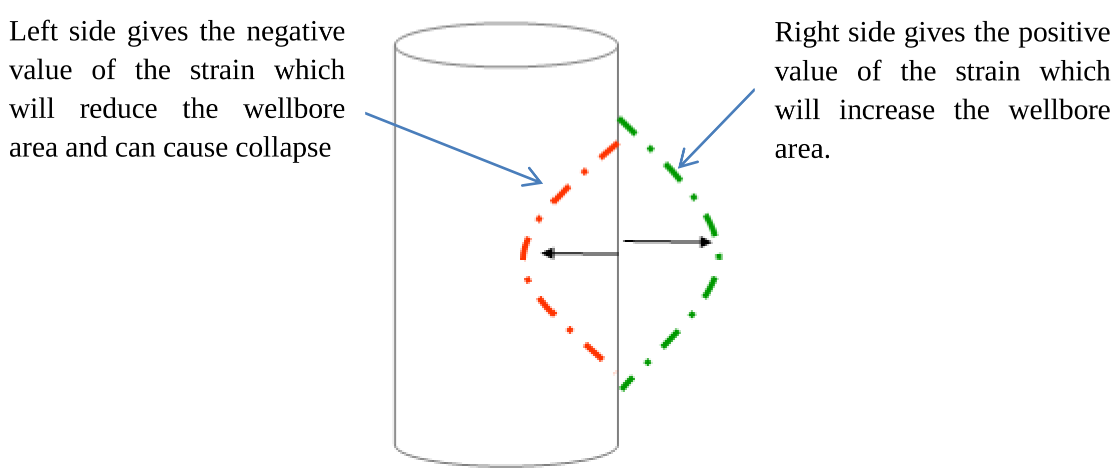


Figure 24: Movement of the strain

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In conclusion, the optimum injection rate of 10000 stb/day can optimize the oil recovery especially for the heavy oil. As for the one dimensional test which is conducted to investigate the effect of water molecules on the alteration of clay minerals is not really achievable as the sample is mainly contain of sand and only contain the small amount of clay. However, the test still can show the effect of the interaction between the water molecules and clay mineral as there are still having the reduction of the void ratio as the effective stress applied is increased.

5.2 Recommendation for future works

To get the best result for this project, steam injection equipment should be available because simulation cannot give the actually result for the clay alteration in EOR well. Besides, X-ray diffraction (XRD) method also should be done to confirm the formation damage that causes the reduction of the permeability due to clay swelling. In addition, others parameter such as the enthalpy of the steam or heat utilization factor can done to get the optimum value that can maximize the oil recovery in clay formation by using cyclic steam injection.

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APPENDICES