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Lab Scale Studies: Modeling of Compaction Pressure effect on Permeability of Synthetic Sandstone Cores

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15819

Dissertation submitted in partial fulfilment of the requirements for the Degree of Study (Hons) (Petroleum)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to
Petroleum Engineering program
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Approved by,

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Mr. ASIF ZAMIR

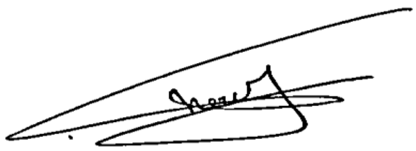
UNIVERSITI TEKNOLOGI PETRONAS

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



SHERIF ABDELHAMID MAHMOUD

ABSTRACT

In petroleum industry, knowing the properties of the rock formation is an essential step and requirement before any job e.g. exploration or drilling and the selection of equipment. Also it's of great importance to understand the effect that some factors have on different aspects and properties of the rock formation. Defining the relationship between the rock formation permeability and the compaction pressure acting upon it, helps facilitate the work on the rock formation and also allow modification and enhancing the production. Therefore, a simplified equation to define this relationship has a great advantage and is highly required. This study is aiming to define and verify the nature of the relationship between the permeability of the rock formation and the compaction pressure acting on the formation and the ratio by which the pressure causes the permeability to decrease. Then a mathematical model will be produced to provide a simplified understanding to that relationship at certain conditions.

ACKNOWLEDGEMENT

Upon finishing this colossus work, it became obvious that there is no amount of gratitude enough to satisfy the help and assistance received during the execution of the project.

First I should show my greatest gratitude to God without whom this project would not have seen the light of day. Then I would like to thank my parents for their help and assistance in the time when hope seemed impossible and out of reach.

I also would like to extend a hand of gratitude to Mr. Asif Zamir my supervisor for his great inputs on the project and his insights on how the project should proceed. Also I would like to thank him for his understanding of my shortcomings and mistakes during the course of the project.

I thank my beloved university UTP and the petroleum engineering department for giving me that chance to do such an important project and provide me with the facilities needed if possible.

Finally I would like to apologize for any party not mentioned in this acknowledgement. I thank all the parties that had even the smallest part to play in making this project reach the stage it is in at this point of time, and I would like to hope for their assistance to continue with others who might work on an improvement on this project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 Background Study

Permeability is the measurement of the rock or formation capability to transmit fluids through the pores. The concept of permeability was first introduced by Henry Darcy (1803-1858). Permeability of the rock formation is a great contributor to the velocity at which fluids transfer through the rock formation. Formations such as sandstone transmit fluids rapidly because of its high permeability since it is a highly porous formation. Unlike sandstone, formations like Shale and Silt have finer grain sizes and when sorted the grains tend to get closer to each other, which decrease the pores throat sizes leading to a lower values of permeability and slower transmission of fluids [1].

Permeability is a factor proposed in the proportionality constant in Darcy's law that propose a relation between the flow rate of a fluid and its physical properties (e.g. viscosity)   and the pressure gradient applied to the formation.

$$K=\upsilon \frac{\mu \Delta x}{\Delta p} \tag{1.1}$$

Where:

υ is the superficial fluid flow velocity through the medium (i.e., the average velocity calculated as if the fluid were the only phase present in the porous medium) (m/s).

K is the permeability of a medium (m^2).

μ is the dynamic viscosity of the fluid (Pa.s).

ΔP is the applied pressure difference (Pa).

Δx is the thickness of the bed of the porous medium (m).

In naturally occurring materials, permeability values range over many orders of magnitude [2].

The concept of permeability is of grave essentiality in the field of oil and gas industry for it is a main identifier of the flow properties of hydrocarbons in reservoirs and underground water in aquifers.

100 md permeability is considered the minimum limit for a rock to be accepted as an exploitable hydrocarbon reservoir. If the formation has a lower permeability, it can be considered as a seal or as a trap formation with a possibility of finding hydrocarbons trapped underneath [2].

1.2 Problem Statement

Permeability has many factors affecting its value in a rock formation. Some of the factors affecting permeability can be related to the rock formation itself e.g. the grain sizes and shape, and the cementation of the rock. Other factors can be related to the location and depth of the rock formation.

This study is concerned with the effect that the compaction pressure play on the permeability. As the compaction pressure on the rock increases, the pore sizes decrease between grains and some of the pore spaces will disconnect and get isolated, this will cause a significant reduction in the permeability of the formation. So there is a reversely proportional relationship between permeability and compaction pressure. Artificial sandstone cores will be subjected to various values of compaction pressure, then the change on the value of the rock permeability will be observed and modeled.

At the end of this project, a number of equations will be submitted describing the relationship between the permeability of the rock formation and the compaction pressure acting on it for both linear and nonlinear formations.

1.3 Objectives and Scope of Study

The first objective of this study is to verify the relationship between the permeability of the rock formation and the compaction pressure acting upon the formation. After satisfying the first objective and finding the required relationship, the second objective will be to formulate and model equations to further facilitate the relationship.

As it was mentioned above, there are many factors affecting the value of the permeability of the rock formation, however the compaction pressure can be considered one of the most affecting factors. So artificial sandstone cores with constant geophysical properties (e.g. porosity, cementation concentration and grain size) will be prepared for the project.

This project is feasible and relevant to the petroleum engineering course as it acknowledge one of the most important concepts in the field of oil and gas. At the end of the project, a working model must be derived to describe the relationship of the permeability and the pressure.

CHAPTER 2
LITERATURE REVIEW

2.1 Sandstone

Sandstone is a clastic sedimentary rock with grains at the size of sand particles. It implies consolidated sand or a rock made from predominantly quartz sand. Sandstone is the most common sedimentary rock on earth. It has relatively high values of porosity and permeability which labels sandstone as a great reservoir rock [3].

“Sand” in sandstone does not mean that the rock is made essentially of sand but rather is refers to the size of the particles forming the rock. The grain size of the particles forming sandstone range from 1/16 millimeter to 2 millimeter. sandstone usually contains mineral, rock and organic particles with varying percentages according to the location of the sandstone [4].

Figure 1 Sandstone Sample

However due to the variation on the composition of the sandstone and the wide range of grain sizes, some of the geophysical properties of the sandstone vary as well.

2.2 Permeability

Permeability is greatly affected by the variation of the composition of sandstone. There are many factors that disturb the permeability.

- Grain Size and Sorting.
  When grain size vary, the relatively smaller grains will occupy the pore spaces between the larger grains which will reduce the volume of paths through the rock. Also if the grains are badly sorted, the interconnected spaces will decrease. Both irregularities cause the reduction of the porosity thus the reduction of permeability.
- Cementation concentration.
  Cement only affect the spaces between the finer grains, which means that it doesn't have a significant effect on the porosity or permeability. However, if the content of cement exceeds 5% of the rock, it starts to cause the porosity and permeability to decrease [5, 6].
- Compaction pressure.
  By increasing the compaction pressure acting upon a rock formation, the rock grains get compacted by re arranging themselves and also some sharp edges and irregularities in the grain shape get broken down and fill the pore spaces between grains. This cause the closing of some paths and reduction in the permeability [5, 7].

2.3 Artificial Sandstone Cores.

Due to these factors, it was impossible to work with natural sandstone cores. But rather it is better and simpler to use Artificial sandstone Cores. The Artificial sandstone Cores will have constant grain size with well-rounded shape and a constant amount of cement concentration, so that the only two variables on the experiment are permeability and compaction pressure [5].

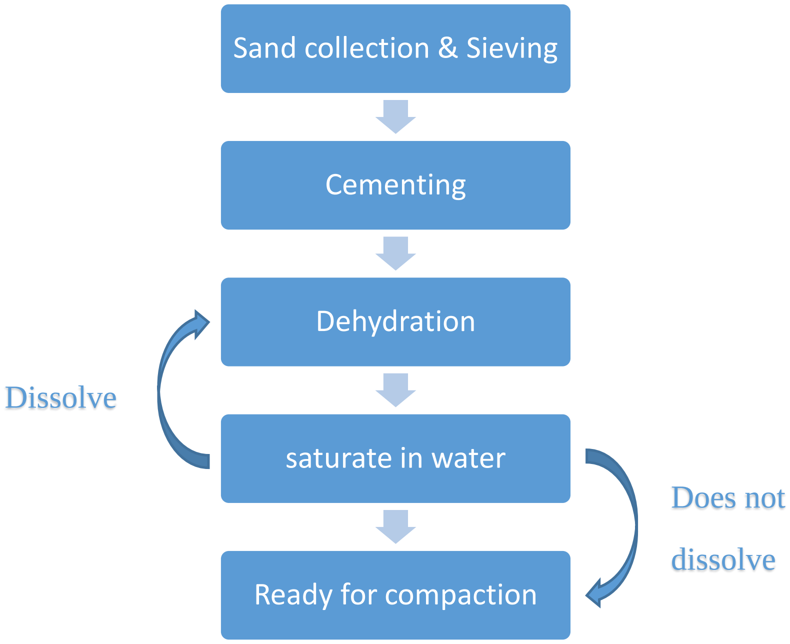


Figure 2 Artificial Sandstone Processing

2.4 Permeability versus Pressure

As mentioned before, on applying pressure to the sandstone, the arrangement of the particles change and the stone is compacted to a relatively smaller size. This causes the pore spaces to shift and get smaller as well leading to a lower porosity and subsequently a lower permeability.

So it is safe to mention that the permeability of a rock formation is inversely proportional with the compaction pressure acting on it [7, 8]

According to Thomas and Ward (1972) the gas permeability of a tight sandstone Core is reduced dramatically on increasing the overburden or the compaction pressure. At 3000 psi, the highest reduction is observed, the permeability of non-fractured core samples drop to a range of 14 – 37% of the initial permeability. For the fractured core samples, the permeability takes a huge loss and can reach only 6% of the initial permeability [9].

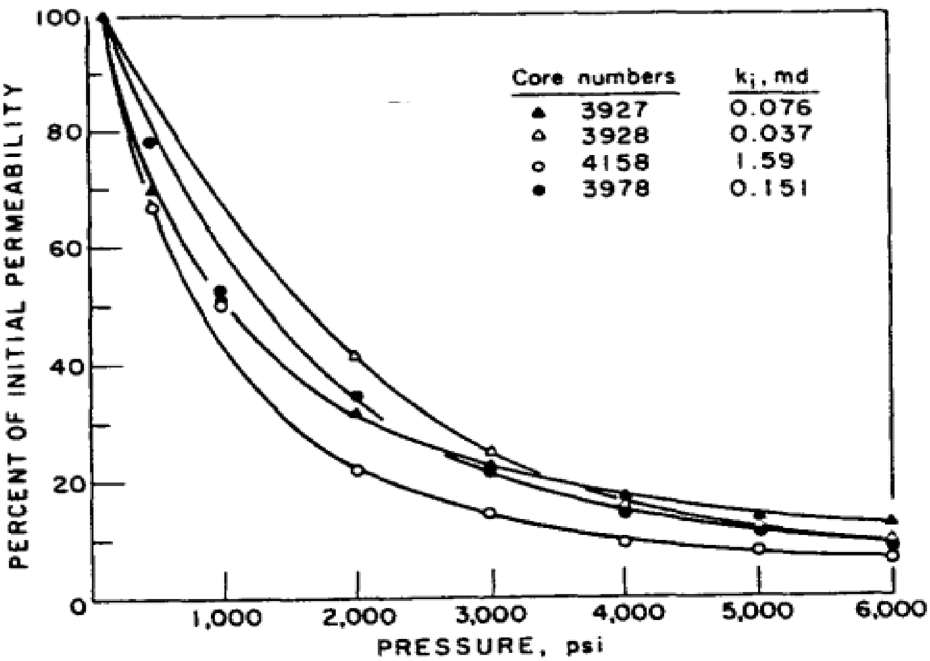


Figure 3 Permeability vs Pressure

This figure shows the effect of compaction pressure on the gas permeability of Gasbuggy cores taken at different depth and have varying porosities.

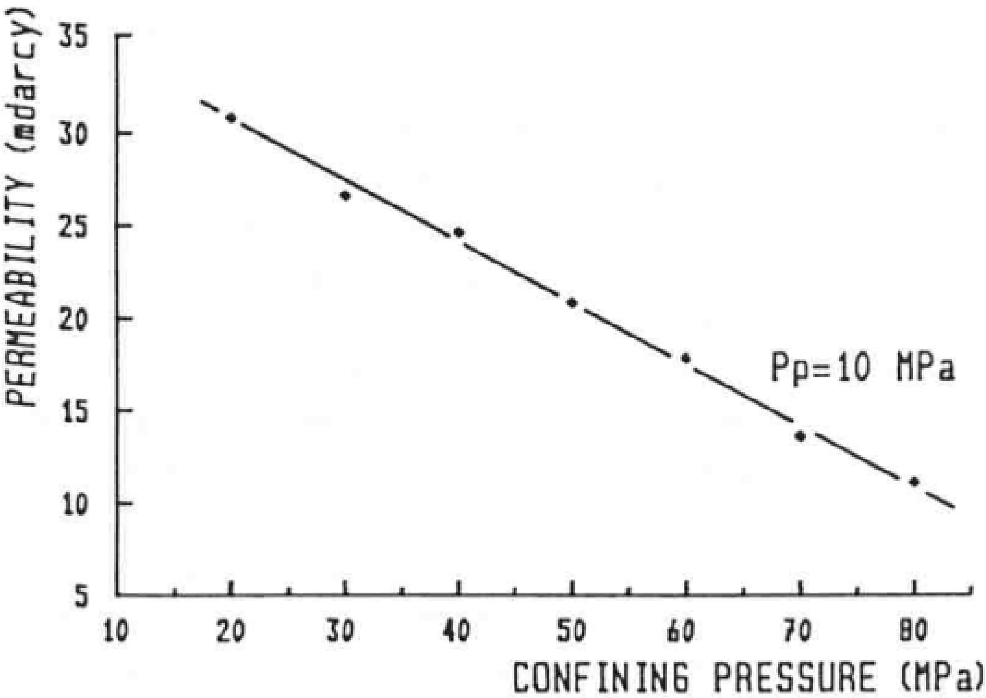


Figure 4 Permeability vs Pressure 2

The above figure describes the effect of confining pressure (compaction pressure) on the permeability of Fontainebleau sandstone core sample. It is a well sorted sandstone with more than 99% of its mineral content consists of quartz and has a grain size of 250 µm. The sample has a bulk porosity of 12.3% and with relatively homogeneous similar very large pores paces [10].

Muhammadu Aruna (1976) stated that the absolute permeability in a porous medium was measured according to the regulations of API on the assumption that if the viscous flow in the medium is dominant, then the absolute permeability depends on the parameters acting on the medium and completely independent and detached from the properties of the fluid filling the medium except for the case of gas flow where the slip effect is taken into consideration. He argued that the absolute permeability of the medium is a function in the change of overburden pressure and the temperature change.

Aruna ran experiments on a large number of samples from consolidated Massillon sandstones and unconsolidated Ottawa Sandstone with four different fluids; nitrogen gas, water, oil, and 2-octane fluid. These experiments aimed to discuss the effect of the increase in the confining pressure and the change in temperature have of the permeability of the rock.

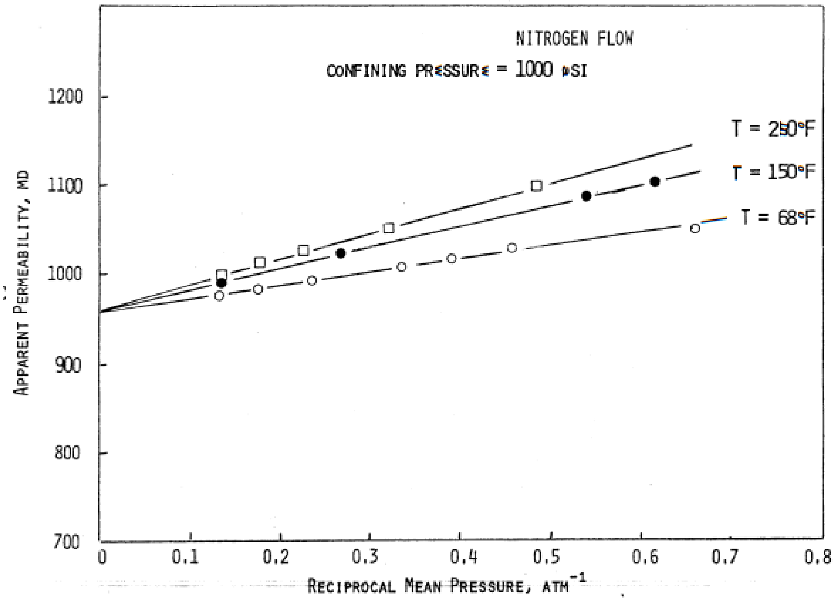


Figure 5 confining pressure vs permeability of Massillon consolidated Sandstone

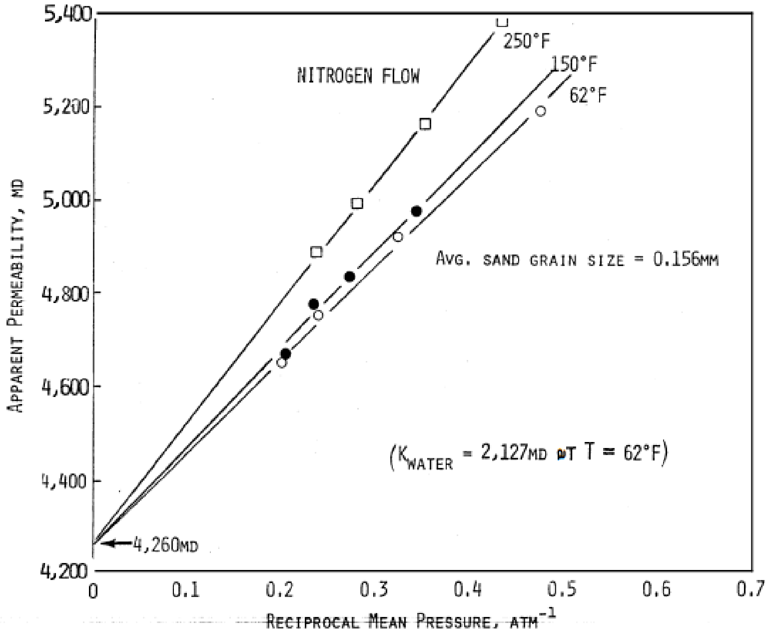


Figure 6 confining pressure vs permeability of Ottawa unconsolidated Sandstone

Figure 5 and **figure 6** show the effect of the increase of the over burden pressure on the permeability of the sandstone cores of consolidated Massillon sandstone and unconsolidated Ottawa sandstone respectively. Muhammadu showed that in both experiments, any increase in the pressure is faced with an increase in the permeability no matter what kind of fluid exists in the medium or the temperature surrounding the medium. He stated that even though during the unconsolidated experiment, the permeability of the rock when using water flow at temperature 62 ^{o}F reached 2127 md as opposed to 4260 md for the nitrogen flow at the same temperature, the effect of the increase in pressure is the same throughout all the fluids [11].

CHAPTER 3
METHODOLOGY

3.1 Research Methodology

Due to complications faced during the project activities, the data for the relationship between the confining pressure and the permeability of sand stone for this project could not be provided. So the data provided by **Mr. Ibrahim Ahmed Ahmed Gawish** in his research "**Characterization of Locally Produced Synthetic Sandstone Cores as Substitute for Imported Berea Sandstone in Research and Student Laboratory Work**" (2012) submitted to King Saud University was acquired and used. The data provided by Mr. Ibrahim matched the primary part of the research parameters set for this project, so it is ready to be used for the modeling process in this project [12].

The following part will record the methodology used by Mr. Ibrahim and the continuation with the modeling done by our part.

Figure 7 shows the steps taken in the process for completing the project course. The steps will be described more on the project activities section.

3.2 Project Activities

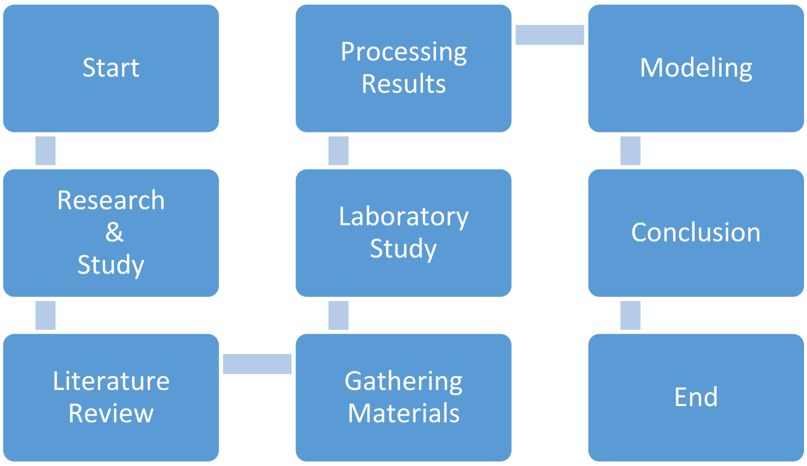


Figure 8 gives a brief description to the project activities to be undertaken throughout the course to achieve the objectives required.

Figure 7 Research Methodology flow

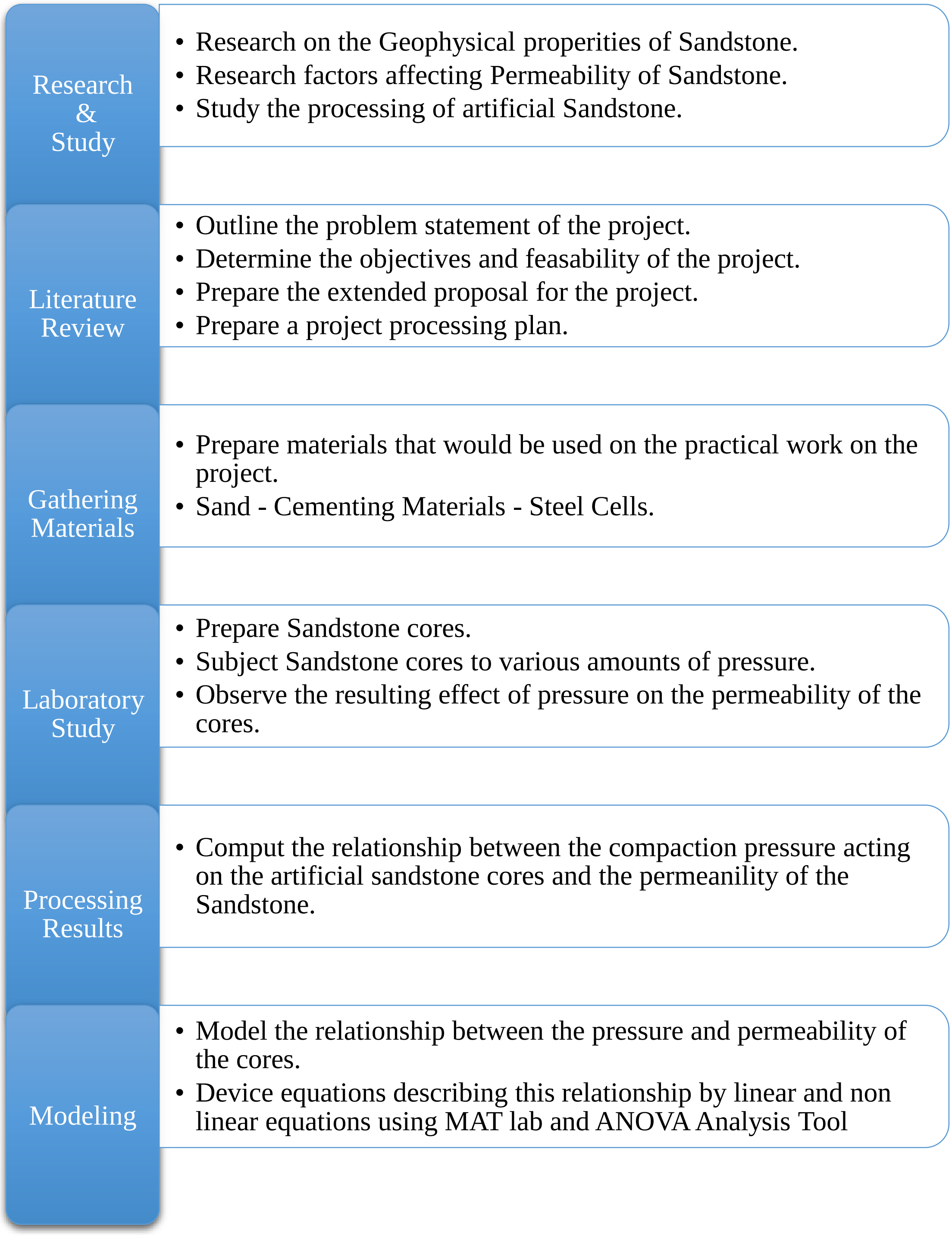


Figure 8 Project Activities

3.2.1. Gathering materials

As it was mentioned before, it is impossible to work with regular natural sandstone cores taken directly from a well because there is no control on the properties and conditions of the sandstone core and this fact will limit if not stop our progress in the laboratory study and work. Therefore, it is of the outmost importance to be in complete control over all the parameters that affect the permeability of a sandstone core so that a relationship can be obtained between the parameters in question (Permeability vs Compaction Pressure) without the fear of the effects caused by the irregularities in other parameters (sand size, sand shape, Cementation).

i. Sand

Sand in the main concentration during the laboratory work. In order to produce a successful sandstone core that will be considered a good match to our criteria, the kind of sand to be used has to be chosen. Control over the sand grain size, grain shape, and grain roundness is needed.

For our experimental work, sand with relatively big grain sizes, with good values of roundness and with a smooth shape with as little irregularities as possible is needed. Considering all these criteria, sand was collected from the area of Kharje 80 km south of Riyadh.

This area was chosen for the collection of sand due to its sand grain sizes where only 2% of the sand fall under 75 µm and only 15% are larger than 500 µm.

ii. Sodium Silicate

Sodium silicate or liquid glass (sodium silicate SiO_2:Na_2O) of specific gravity of 1.4 and a 3.2: 1.0 of SiO_2: Na_2O ratio was the cementing agent to be used throughout this experiment in the manufacturing of the sandstone cores.

This cementing agent was used instead of calcite because the grains cemented by calcite cementing agents are loosely packed which makes them not safe or efficient for compaction,(chilingarian 1976).

iii. Compaction steel cells

The steel cells were used in order to hold the sandstone cores in place when compaction and to make sure that no fluid escape the core during the process of compacting the cores.

There were two steel cells:

- Compacting cell

This cell had an internal diameter equal to that of the core 3.8 cm diameter and 6.5 cm length. This cell was responsible of holding the core in place when it is compacted.

- Receiver cell

This cell had an internal diameter slightly larger than that of the compacting cell. This cell was used to receive the core after molding and after compaction.

3.2.2. Laboratory Work

This experiment was conducted on three steps. The following figure will summarize those steps taken in order to verify the final relationship between the permeability of sandstone and Compaction pressure.

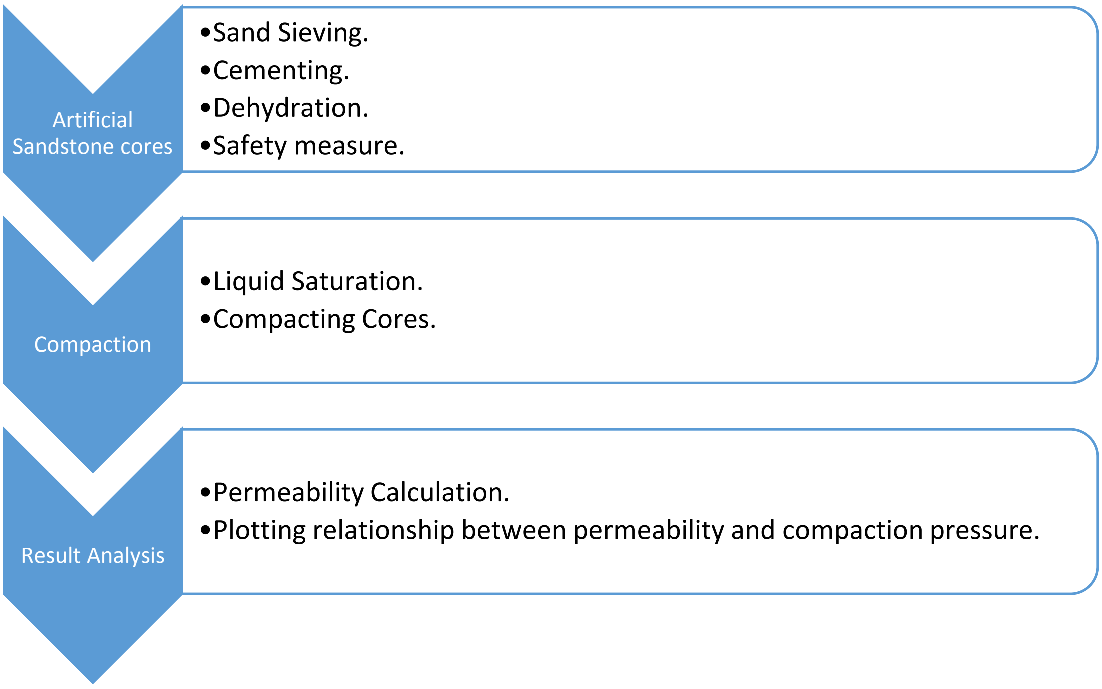


Figure 9 Flow of Experiment

i. Artificial Sandstone Cores

- Sand Sieving

First step in the manufacturing artificial sand stone is choosing the appropriate sand grain size. The sand collected was processed through the sieving machines to categorize the sand by grain size and to remove any organic material or clay residue in the sand. A suitable range of grain sizes was chosen according to the size distribution on the sand. Seven samples were made with a grain size that falls in the range of 355-300 µm with diameter of 3.8 cm and 6.0-6.5 cm in length.

- Cementing

After the sieving of the sand and the selection of the sand to be used for the rest of the experiment, a portion of the sand would be placed in the compaction cell and an amount of sodium silicate equal to 7% of the volume of the sand in the cell was mixed with the sand. The core then was compacted to the desired confining pressure using uniaxial compressive apparatus. The compaction pressure ranged from 14500 – 26000 psi.

- Dehydration

The mixture will then be put in an oven under the temperature of 300^{o}c in order to dehydrate the mixture, crystalline the cementing agent (sodium silicate), solidify the core and prevent the solution of the cementing agent in the flooding fluid. 300^{o}c is the crystallization and solidification temperature of the cementing agent and it is the point when there is no more weight loss which means that vaporization of all the loss water in the samples.

ii. Compaction

- Liquid saturation

The cores were vacuumed by a core vacuuming device, and then it was saturated with liquid of known viscosity (water). Then it was ready for core flooding and permeability measurement.

iii. Results Analysis

- Permeability calculation

The permeability of the cores was calculated by the core flooding machine. After the calculation, a permeability value corresponding to each value of pressure throughout the range of pressures proposed is obtained. The data obtained is displayed in **Appendix 1**.

A graph of sandstone permeability against compaction pressure is plotted according to the obtained values. This graph represents the permeability-compaction pressure relationship.

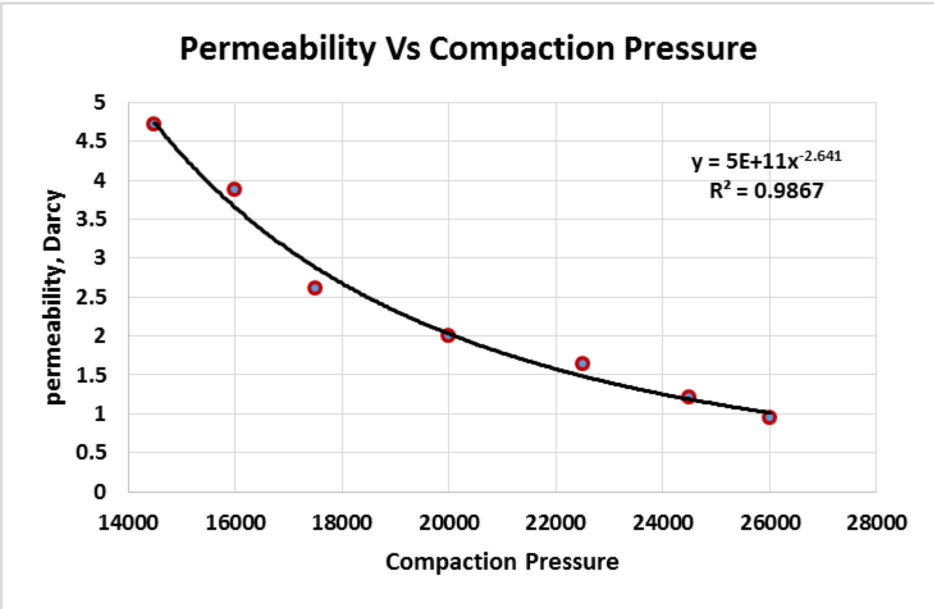


Figure 10 Compaction Pressure vs Permeability

3.3 Modeling

The final step of the project comes after the final graph that represents the relationship between the permeability of synthetic sandstone cores and the compaction pressure acting on the core. Two mathematical models are developed to further describe and facilitate this relationship. Those models will be done by two different simulators; MATLAB software and ANOVA software done by MICROSOFT.

3.3.1. MATLAB software

MATLAB or matrix laboratory is a high-level language and interactive environment for numerical computation, visualization, and programming. It is a multi-paradigm numerical computing environment and fourth-generation programming language, created by MathWorks. By using MATLAB, it became easy to create models describing numerous relations, create applications, develop algorithms and analyze data with great precession and speed.

Although MATLAB is intended primarily for numerical computing, an optional toolbox uses the MuPAD symbolic engine, allowing access to symbolic computing capabilities. An additional package, Simulink, adds graphical multi-domain simulation and Model-Based Design for dynamic and embedded systems. The language, tools, and built-in math functions enable exploring multiple approaches and reach a solution faster than with spreadsheets or traditional programming languages, such as C/C++ or Java.

MATLAB can be used for a range of applications, including signal processing and communications, image and video processing, control systems, test and measurement, computational finance, and computational biology. More than a million engineers and scientists in industry and academia use MATLAB, the language of technical computing.

The first model was done by MATLAB software. The software was feed the data obtained by the experiment and the program in **Appendix 2** was used to interpolate the data and produce an equation that satisfy the relationship.

Once the program was developed, it was time to start obtaining a number of equations with different orders so that they can be compared and decided on one of them with the greatest proximity to the experimental data. This was done by the changing the order of the wanted equation to be produced by changing the variable ***n*** circled in the program in **Appendix 2**.

The model will be used to produce a satisfying linear equation to define the relationship between the compaction pressures and the permeability of sandstone and a non-linear equation defining the relationship. By producing two equations, it will be easier to find the most optimum model to use and create a platform that facilitate the development of the relationship and the equation.

3.3.2. ANOVA software

ANOVA or Analysis of Variance is a plugin used on Microsoft EXCEL. Analysis of variance is a collection of statistical models used in order to analyze the differences between group means and their associated procedures (such as "variation" among and between groups). In the ANOVA setting, the observed variance in a particular variable is partitioned into components attributable to different sources of variation. In its simplest form, ANOVA provides a statistical test of whether or not the means of several groups are equal, and therefore generalizes the t-test to more than two groups. As doing multiple two-sample t-tests would result in an increased chance of committing a statistical type I error, ANOVAs are useful in comparing (testing) three or more means (groups or variables) for statistical significance.

In general, the purpose of analysis of variance (ANOVA) is to test for significant differences between means. Elementary Concepts provides a brief introduction to the basics of statistical significance testing. If only two means are being compared, ANOVA will produce the same results as the t test for independent samples or the t test for dependent samples.

The second model was done by using ANOVA software. The software was feed the same data from **Appendix 1** much like MATLAB. Then the ANOVA Single Factor Regression tool will be used to show the significance and the effect of the factors on each other, also it will give the coefficients that will be used in the linear equation as it is shown in **Appendix 3**.

After the Single Factor Regression tool is completed, ANOVA Power Regression is used to provide an exponential non-linear equation that defines the relationship as it is shown in **Appendix 4**.

3.4 Key Milestones

The following figure show the main Key Milestones faced during the duration of the final year project 2.

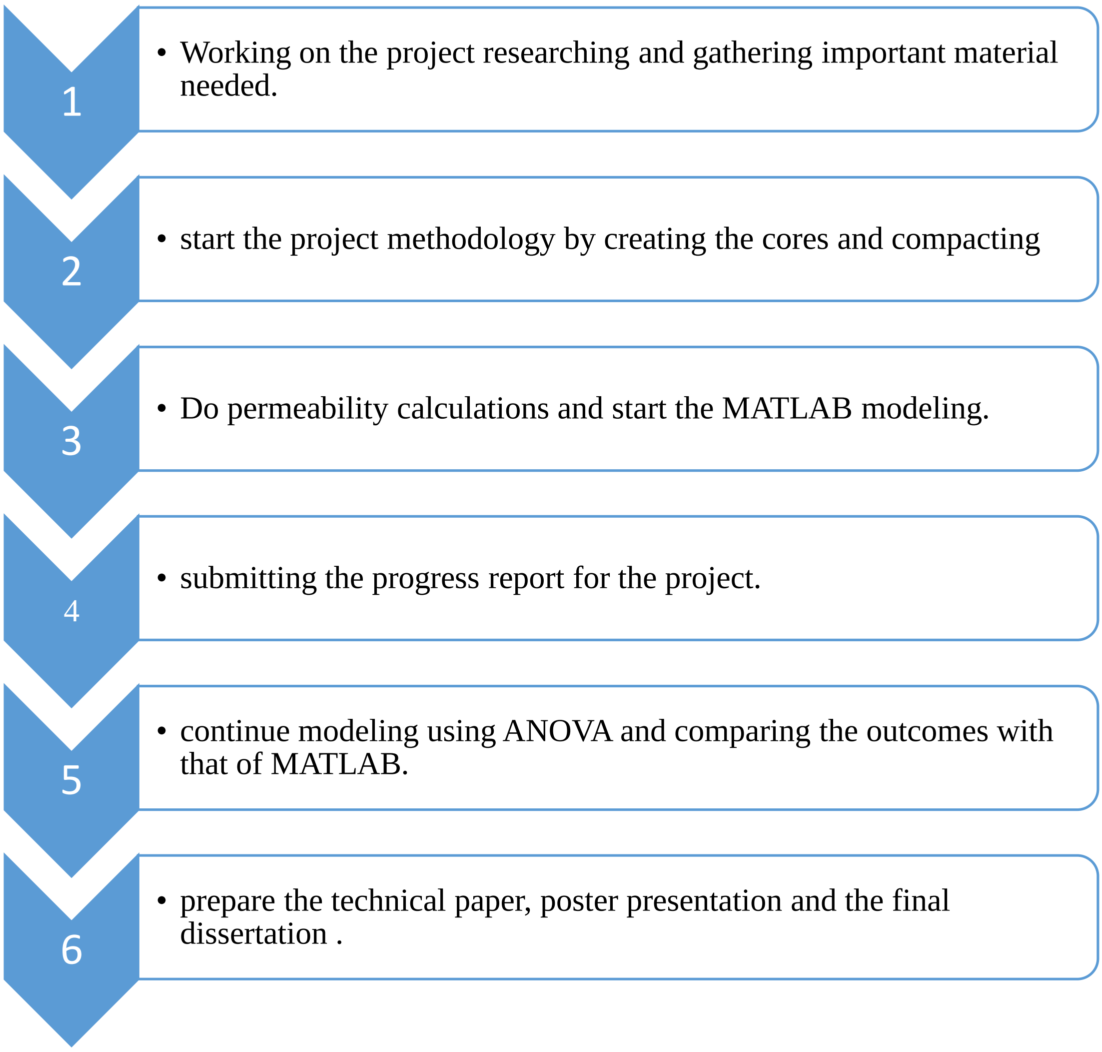


Figure 11Key Milestones

3.5. GANNT CHART

Table 1 Gantt Chart FYP I

DETAILS	WEEKS												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Selecting Topic													
2. Researching the Project													
3. Preparation for Extended Proposal.													
4. Submission of Extended Proposal.													
5. Preparing for Proposal Defense.													
6. Proposal Defense and Evaluation.													
7. Preparation for Interim Report.													
8. Submission of Interim Report.													

Table 2 Gantt Chart FYP II

DETAILS	WEEKS												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Booking laboratories and securing the remaining materials.													
2. Artificial Sandstone manufacturing.													
3. MAT lab modeling													
4. Submitting progress report.													
5. ANOVA modeling													
6. Poster presentation													
7. Submission of final report, dissertation, and technical paper.													
8. Viva.													

CHAPTER 4
DISCUSSION & RESULTS

4.1 Results

4.1.1 MATLAB

After applying the code in **Appendix 2** in MATLAB with different values for the variable ***n*** which represents the order of the equation wanted to be obtained, a number of equations that describes the relationship between the compaction pressure and the permeability of sandstone can be obtained. Described below are the equations obtained by normal iterations of the data provided by the experiment. These equations will be linear equations with different orders.

Then a different approach was used to find the non-linear equations. The curve fitting tool box is used. The data was feed to the tool and the appropriate form of an exponential equation was chosen as shown in **Appendix 5**. The resulted plot and equation is recorded in the non-linear part of the results.

Where;
K is the permeability of sandstone (Darcy).
P is the applied pressure difference (Psi).

4.1.1.1. Linear equation

- First order equation n = 1.

$$K = aP + b \tag{4.1}$$

Table 3 coefficients for 1st order equation

a	b
-3.063809E-04	8.603002

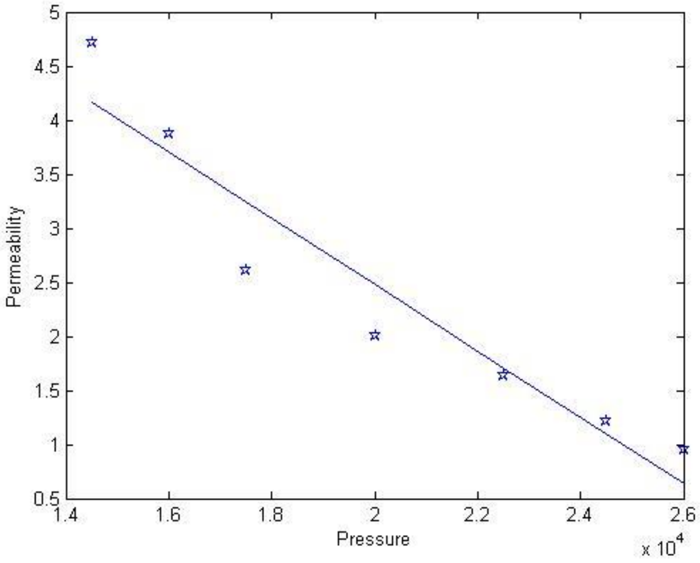


Figure 12Permeability vs Pressure (1st order equation)

Table 4 Permeability from 1st order equation

Pressure	Permeability (experiment)	Permeability (modeling)	Error (%)
14500	4.719228	4.160478	11.8
16000	3.878010	3.700906	4.6
17500	2.618025	3.241335	23.8
20000	2.004896	2.475383	23.5
22500	1.636650	1.709430	4.4
24500	1.216081	1.096668	9.8
26000	0.948407	0.637097	32.8

- Second order equation **n = 2**.

$$K = aP^2 + bP + c \tag{4.2}$$

Table 5 coefficients for 2nd order equation

a	b	c
2.804893E-08	-0.001443	19.65849

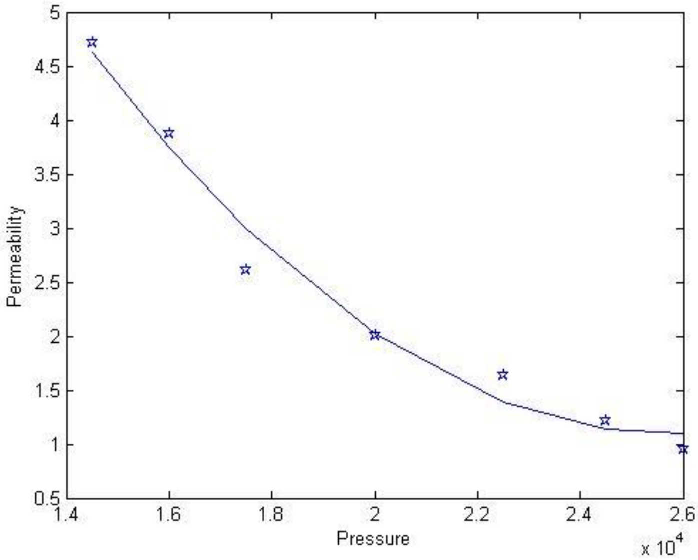


Figure 13 Permeability vs Pressure (2nd order equation)

Table 6 Permeability from 2nd order equation

Pressure	Permeability (experiment)	Permeability (modeling)	Error (%)
14500	4.719228	4.631279	1.9
16000	3.878010	3.749913	3.3
17500	2.618025	2.994769	14.4
20000	2.004896	2.016683	0.6
22500	1.636650	1.389209	15.1
24500	1.216081	1.139670	6.3
26000	0.948407	1.099773	16

- Fourth order equation **n = 4**.

$$K = aP^4 + bP^3 + cP^2 + dP + e \qquad (4.3)$$

Table 7 coefficients for 4th order equation

a	b	c	d	e
-2.776538E-16	1.869504E-11	-4.147702E-07	2.811755E-03	6.491110076

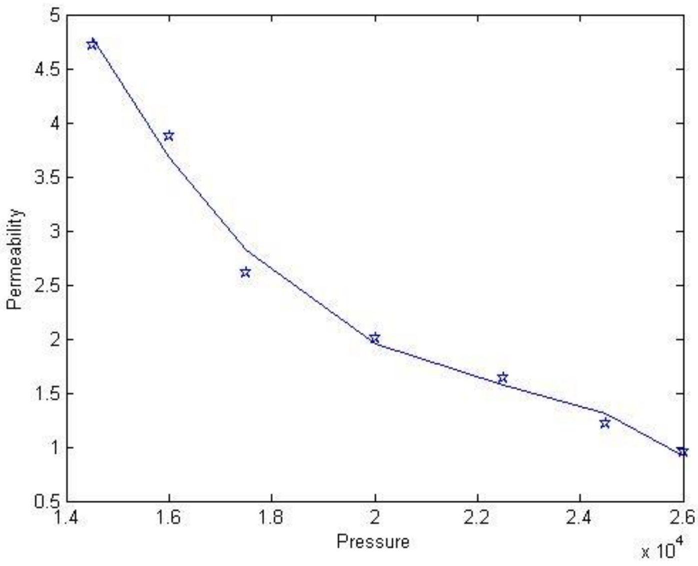


Figure 14 Permeability vs Pressure (4th order equation)

Table 8 Permeability from 4th order equation

Pressure	Permeability (experiment)	Permeability (modeling)	Error (%)
14500	4.719228	4.776589	1.2
16000	3.878010	3.676587	5.2
17500	2.618025	2.826294	8
20000	2.004896	1.953850	2.5
22500	1.636650	1.566752	4.3
24500	1.216081	1.306223	7.4
26000	0.948407	0.915002	3.5

- Sixth order equation **n = 6**.

$$K = aP^6 + bP^5 + cP^4 + dP^3 + eP^2 + fP + g \qquad (4.4)$$

Table 9 coefficients for 6th order equation

a	b	c	d	e
-9.133515E-23	11.478422E-18	-596.08063E-15	16.361870E-09	-250.188365E-05
f	g			
2.018705	-6.704305E+003			

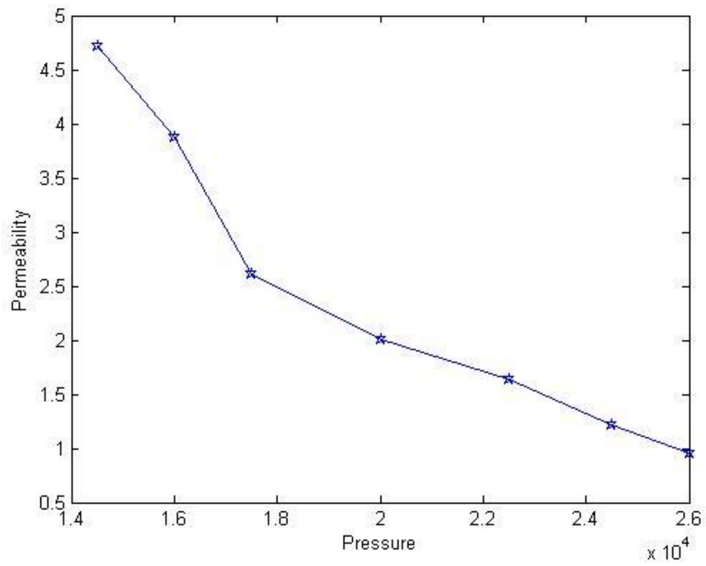


Figure 15 Permeability vs Pressure (6th order equation)

Table 10 Permeability from 6th order equation

Pressure	Permeability (experiment)	Permeability (modeling)	Error (%)
14500	4.719228	4.719228	0
16000	3.878010	3.878010	4E-9
17500	2.618025	2.618025	1E-8
20000	2.004896	2.004896	14E-9
22500	1.636650	1.636650	9E-9
24500	1.216081	1.216081	3E-9
26000	0.948407	0.948407	3E-8

- Seventh order equation **n** = **7**.

$$K = aP^7 + bP^6 + cP^5 + dP^4 + eP^3 + fP^2 + gP + h \quad (4.5)$$

Table 11 coefficients for 7th order equation

a	b	c	d	e
4.232518E-29	-2.088202E-24	2.579898E-20	0	0
f	g	h		
0	0	0		

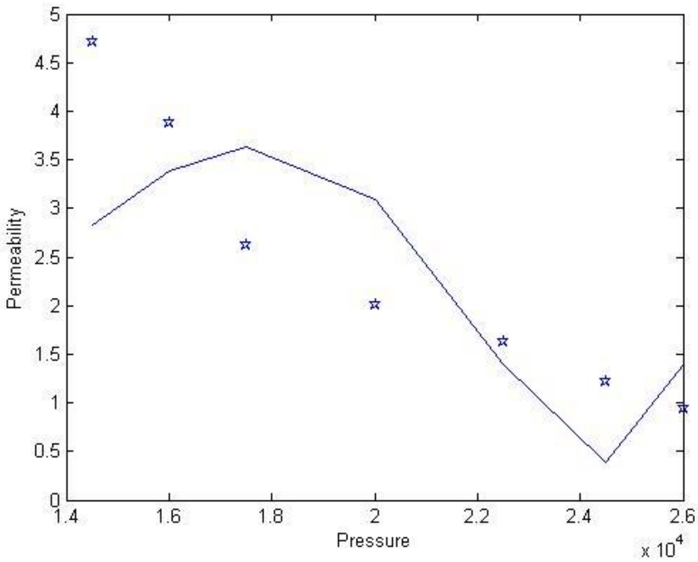


Figure 16 Permeability vs Pressure (7th order equation)

Table 12 Permeability from 7th order equation

Pressure	Permeability (experiment)	Permeability (modeling)	Error (%)
14500	4.719228	2.832405	40
16000	3.878010	3.379545	12.9
17500	2.618025	3.639638	39
20000	2.004896	3.088005	54
22500	1.636650	1.392876	14.9
24500	1.216081	0.385828	68.3
26000	0.948407	1.396503	47.2

As it is obvious from the previous graphs and tables. In the linear regression analysis, the accuracy of the equation increases dramatically as the order of the equation increases. This increase in accuracy is true up until a certain value where the equation is no longer able to fit the results and the equation if deviating from the desired trend line. For these results, the sixth order is the maximum order that can describe the set of data obtained in the project. So starting from the seventh order, the equation deviate drastically from the data points.

However it is also obvious that as the order of the equation increase, the equation becomes more and more complicated and tend to be harder to be used.

That is why only the first order equation will be used in the project as a linear equation, and the model will be modified to create non-linear exponential equations which would better describe the relationship.

4.1.1.2. Non-linear equations

By using the exponential regression in the curve fitting tool in MATLAB, this curve is found to have the best fit.

$$K = a * e^{b*P} + c * e^{d*P} \tag{4.6}$$

Table 13 coeffecients of non-linear equation

a	b	c	d
229.4	-0.000325	9.751	-0.00008828

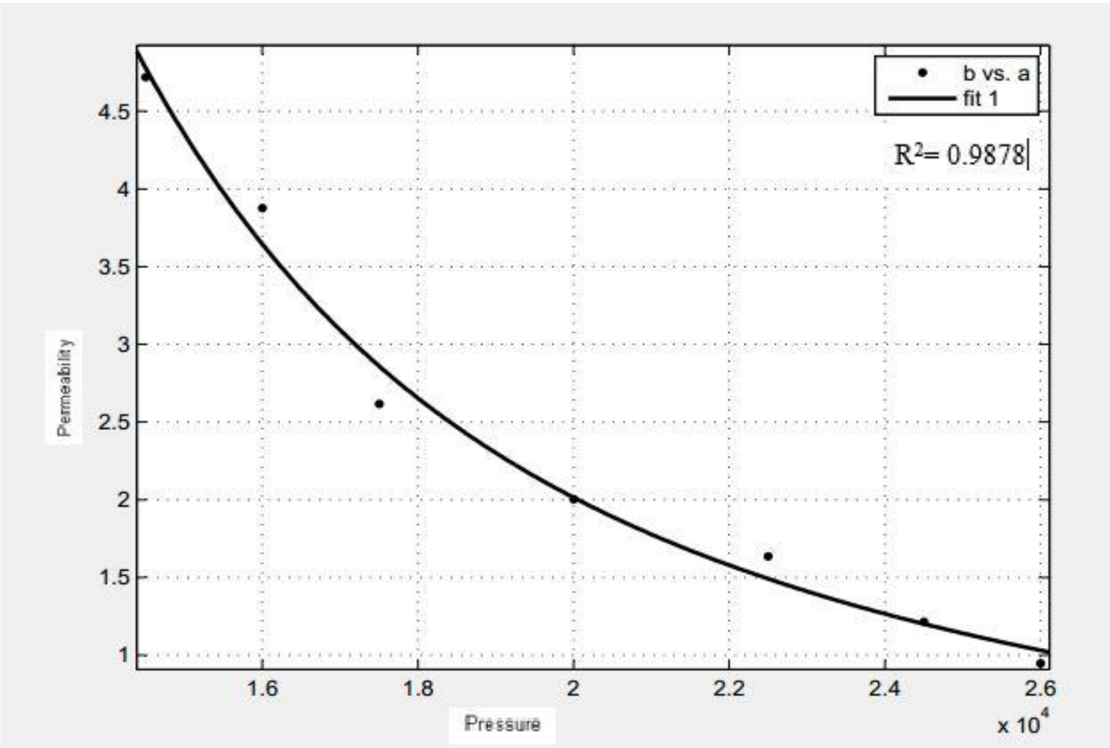


Figure 17 MATLAB Non-linear Equation

Table 14 Permeability from Non-linear equation

Pressure	Permeability (experiment)	Permeability (modelling)	Error
14500	4.7	4.778	1.235
16000	3.9	3.644	6.027
17500	2.6	2.860	9.249
20000	2.0	2.015	0.480
22500	1.6	1.492	8.863
24500	1.2	1.202	1.190
26000	0.9	1.032	8.769

4.1.2. ANOVA

The model for ANOVA was created to develop a mathematical realization of the relationship between the permeability of sandstone and the compaction pressure acting on it in two ways; a linear equation and a non-linear equation.

4.1.2.1. Linear equation

The linear equation of the ANOVA model is a first order polynomial equation.

$$K = aP + b \tag{4.7}$$

Table 15 coefficients of ANOVA linear equation

a	b
-0.0003064	8.603001

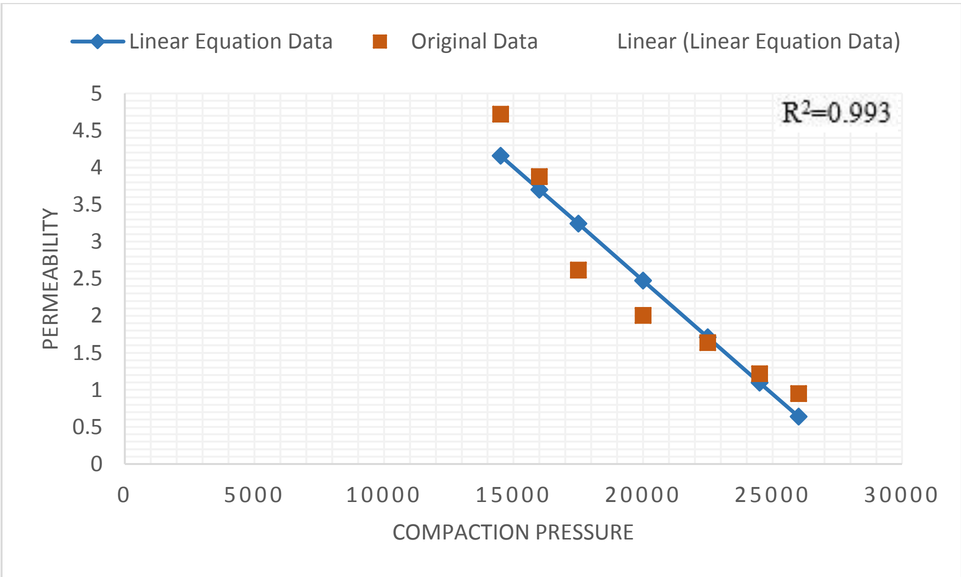


Figure 18 ANOVA linear equation

Table 16 Permeability from ANOVA linear equation

Pressure	Permeability (experiment)	Permeability (modelling)	Error
14500	4.7	4.1605	11.8
16000	3.9	3.7009	4.6
17500	2.6	3.2413	23.8
20000	2.0	2.4754	23.5
22500	1.6	1.7094	4.4
24500	1.2	1.0967	9.8
26000	0.9	0.6371	32.8

4.1.2.2. Non-linear equation

The non-linear model made by ANOVA is a power regression model of equation:

$$K = a * P\hat{}b \tag{4.8}$$

Table 17 coefficients of ANOVA non-linear equation

a	b
4.61904∗(10^11)	-2.6406481

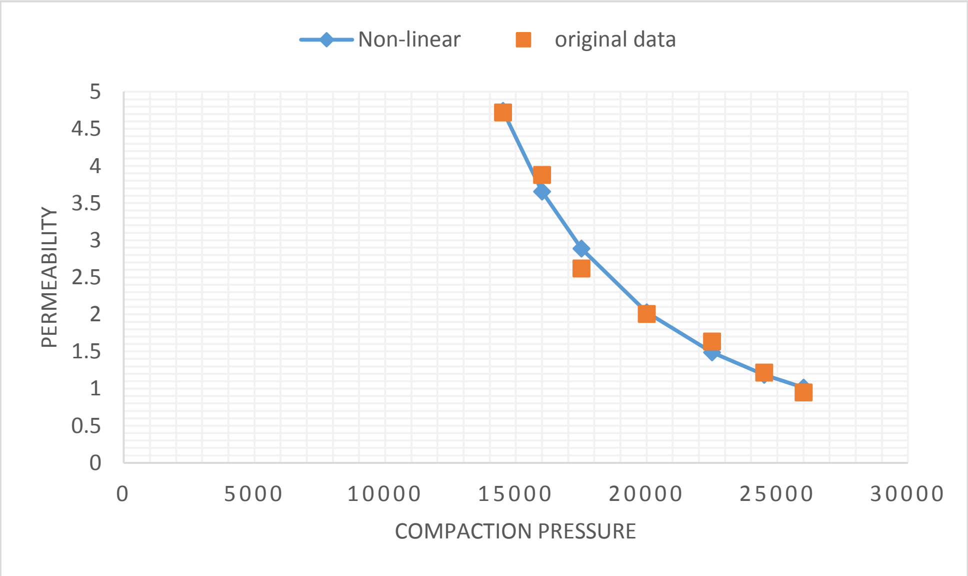


Figure 19 ANOVA non-linear equation

Table 18 Permeability from ANOVA non-linear equation

Pressure	Permeability (experiment)	Permeability (modelling)	Error
14500	4.7	4.7	0.5
16000	3.9	3.7	5.7
17500	2.6	2.9	10.2
20000	2.0	2.0	1.1
22500	1.6	1.5	9.2
24500	1.2	1.2	2.4
26000	0.9	1.0	6.9

4.2 Discussion

By analyzing the data provided by the experiment, a number of equations that can be used to identify the relationship between the compaction pressure acting on a sandstone core and its permeability is obtained. The results above represents the linear polynomial equation of the first, second, fourth, sixth, and seventh order as well as an exponential equation representing the non-linear equation done my MATLAB.

Also there are two more equations representing the linear and non-linear modeling done by ANOVA.

As it was shown from the representations of the MATLAB linear equations in the graphs, as the order of the order of the equation increases, the equations converges more towards the real data provided by the experiment. This is also proved by considering the remarkable decrease in the error percentage between the experiment data and the modeled data by increasing the equation order. This case is valid for the equations of orders 1 to 6. However once an interpolated equation with order higher than 6 is attempted, it is found that the equations diverge with a high rate causing a great deviation in the graph from the experiment data and high error percentages.

It is also noted that, when the order of the equation increases, the equation tends to be more complicated and harder to work with.

By considering that, it can be safely assumed that the linear equation with the first order can be considered the best case to be used to define the relationship between the compaction pressure acting on the sandstone and its permeability. This is because it has a very easy and not complicated representation and the error is not as great as expected.

So by analyzing the data and results obtained by the equations, this table emerges.

Table 19 comparison of results

ORIGINAL		LINEAR				NONLINEAR			
Pressure	**Permeability**	**MATLAB**	**Error *(%)***	**ANOVA**	**Error *(%)***	**MATLAB**	**Error *(%)***	**ANOVA**	**Error *(%)***
14500	4.72	4.160	11.846	4.160	11.840	4.778	1.235	4.741	0.455
16000	3.88	3.701	4.575	3.701	4.567	3.644	6.027	3.656	5.737
17500	2.62	3.241	23.796	3.241	23.808	2.860	9.249	2.885	10.207
20000	2.00	2.475	23.448	2.475	23.467	2.015	0.480	2.028	1.147
22500	1.64	1.709	4.421	1.709	4.447	1.492	8.863	1.486	9.215
24500	1.22	1.096	9.858	1.097	9.819	1.202	1.190	1.187	2.423
26000	0.95	0.637	32.877	0.637	32.825	1.032	8.769	1.014	6.946
	Average Error		**15.83135**		**15.82471**		**5.11594**		**5.1615**

From the previous table, it’s obvious that the modeling done by MATLAB is superior to that done by ANOVA. Hence, MATLAB modeling should be the one used for further development of the project.

CHAPTER 5
CONCLUSION & RECOMMENDATION

5.1. Conclusion

The experiment and the data acquired show the great effect of the compaction pressure has on the permeability of sandstone. With the increase in the pressure acting on a sandstone core, the pore throat sizes decline as grains get closer to each other. This action causes an increase in the absolute permeability of the stone. So the relationship between the absolute permeability of sandstone and the compaction pressure acting on the stone is an inversely proportional relationship. This experiment proves and verifies this kind of relationship with approved set of laboratory data.

These data were obtained by keeping a set of controllable parameters constant so they do not interfere with the experimentation and contaminate the results. These parameters are the cementation concentration in the stone, the average grain size and roundness of the sand, and the temperature acting on the sandstone at the time of compaction.

In the light of the obtained data, a modeling process started to try to model an equation that describes this relationship and facilitates the understanding of the relationship and to be used in the industry.

5.2 Recommendation

It is recommended that in the future, this experiment should be carried out with more variables than the two variables such as; the grain size, the concentration of cement in the core and the temperature of the core, used in this project so it can be used more universally in the benefit of the oil and gas industry.

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APPENDIX

APPENDIX 1

Cementing	7%

Phase	Pressure (Psi)	Sr. No	Size Range	Sorting	L (cm)	D (Cm)	A (cm2)	Tavg (Sec)	V1	V2	V3	Vavg (CC)	Pi	P	dp (psi)	dp(atm)	Q (cc/sec)	μ(cp)	K (darcy)
A	14500	1	355 - 300	1.18	6.5	3.81	11.4	30.00	51	50	51	50.7	0	3	3	0.20	1.69	1	4.7
B	16000	1	355 - 300	1.18	6.4	3.81	11.4	30.00	49	50	50	49.3	0	4	3.5	0.24	1.64	1	3.9
C	17500	1	355 - 300	1.18	6.3	3.81	11.4	30.00	48	49	49	48.3	0	5	5	0.34	1.61	1	2.6
D	20000	1	355 - 300	1.18	6.15	3.81	11.4	30.00	45	46	46	45.5	0	6	6	0.41	1.52	1	2.0
E	22500	1	355 - 300	1.18	6.5	3.81	11.4	30.00	41	41	41	41.0	0	7	7	0.48	1.37	1	1.6
F	24500	1	355 - 300	1.18	6.3	3.81	11.4	30.00	38	38	39	38.2	0	9	8.5	0.58	1.27	1	1.2
G	26000	1	355 - 300	1.18	6.1	3.81	11.4	30.00	36	37	36	36.2	0	10	10	0.68	1.21	1	0.9

```
a=[14500,16000,17500,20000,22500,24500,26000];
b=[4.719228126,3.878010018,2.618025239,2.004895765,1.636649604,1.216080689,0.948407227];
k=polyfit(a,b,n)
format long eng
p1=[14500,16000,17500,20000,22500,24500,26000];
k1=polyval(k,p1);
figure (1)
plot(a,b,'p');
hold on
plot(p1,k1);
```

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.996709287
R Square	0.993429402
Adjusted R Square	0.986858805
Standard Error	0.161112009
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	11.77359815	3.924532716	151.1931548	0.000902398
Residual	3	0.077871238	0.025957079		
Total	6	11.85146938			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	8.603001632	0.308872064	27.85296123	0.000101589	7.620032872	9.585970392	7.620032872	9.585970392
Pressure (Psi)	-0.000306381	1.50331E-05	-20.38040727	0.000258274	-0.000354223	-0.000258539	-0.000354223	-0.000258539

APPENDIX 4

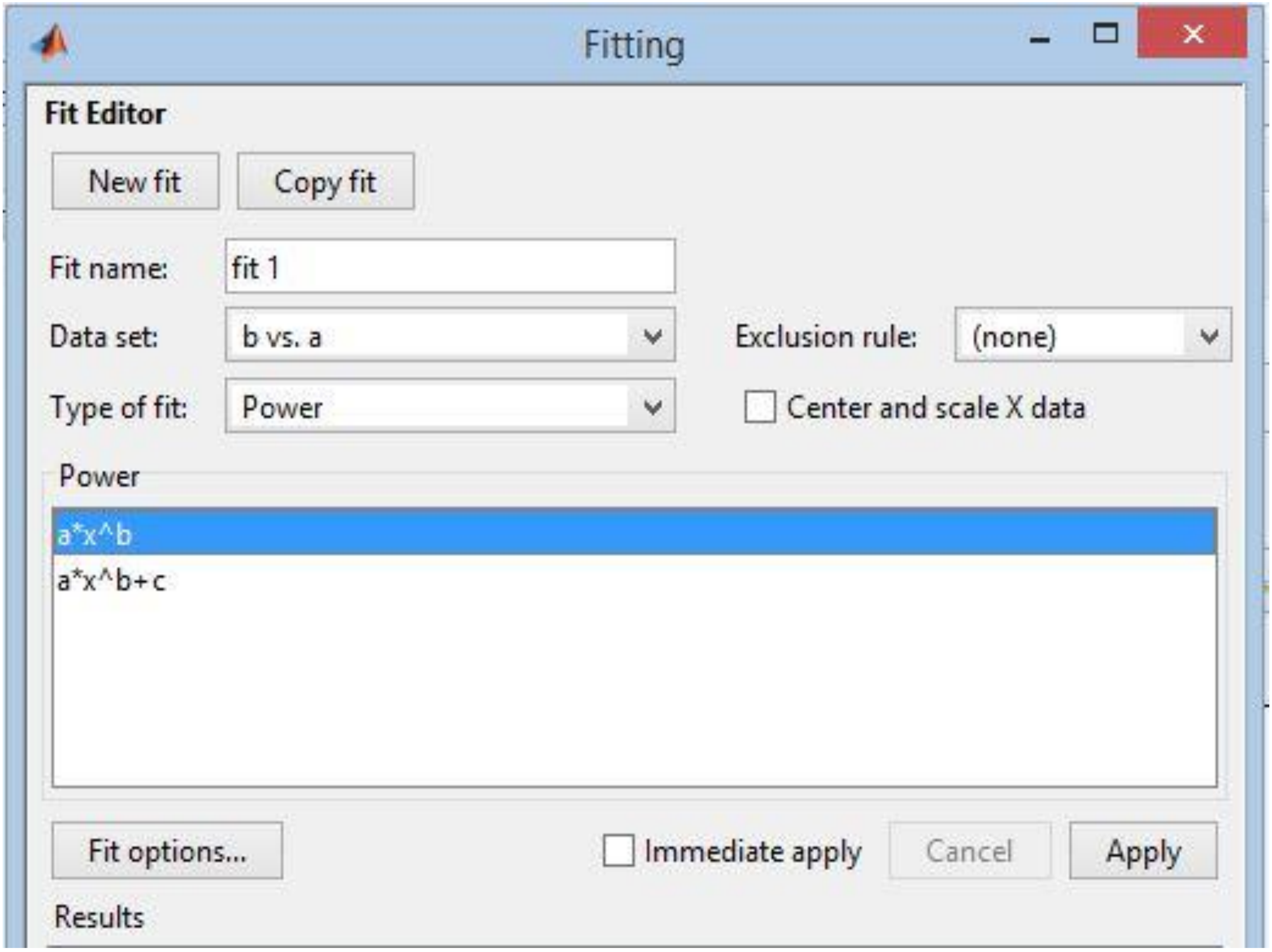
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.995722881
R Square	0.991464055
Adjusted R Square	0.982928111
Standard Error	0.076839407
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	2.057380685	0.68579356	116.151652	0.001335399
Residual	3	0.017712884	0.00590429		
Total	6	2.075093569			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	26.8586229	1.402691172	19.1479232	0.00031107	22.39463356	31.3226122	22.3946336	31.3226122
Pressure (Psi)	-2.6406481	0.141800387	-18.6222912	0.00033797	-3.09192022	-2.18937598	-3.09192022	-2.18937598


Fitting
Fit Editor
New fit
Copy fit
Fit name:
fit 1
Data set:
b vs. a
Exclusion rule:
(none)
Type of fit:
Power
Center and scale X data
Power
a*x^b
a*x^b+c
Fit options...
Immediate apply
Cancel
Apply
Results