VALIDITY OF PERMEABILITY ESTIMATION FROM PUBLISHED CORRELATIONS

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15050

Dissertation submitted in partial fulfilment of

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CERTIFICATION OF APPROVAL

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Approved by,

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January 2015

CERTIFICATION OF ORIGINALITY

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

Ili Nashrin binti Norizam

ABSTRACT

Permeability is classified as one of the most critical properties of the porous medium. In general permeability is defined as its ability to allow fluids to flow rapidly through the rocks. Numerous researchers have proposed empirical models for permeability determination. Over and over again, these relationships are utilized to make vital conclusions without proper regard. Thus, accurate knowledge of permeability in reservoir is very critical. The objective of this study is to identify the validity of selected permeability relationships through correlations of different physical properties.

This study encompasses of two parts. First section of this study is to present the results of identifying the ability of each empirical model with the data available. In view of this, the results of the validation correlations can be known. Hence, further discussion on identifying the problems of invalid correlations with presented data is conducted. Knowledge of appropriate empirical models permits significant permeability relationship comparisons. In this paper, the capability of each empirical model to match with the data available would be the center of this study and to be supported with the explanation of invalid correlations.

From the results, there is no clear relationship of permeability were obtained. The graphical representation will be used as the results and to conclude conclusions.

ACKNOWLEDGEMENTS

First and foremost, all thank and praise to Allah the almighty for His utmost guidance in completing this final year project. I would like to express my indebted gratitude and appreciation to all parties that involved in completing the project. A special thanks and appreciation to my supervisor, AP Dr Syed Mohammad Mahmood, for his time to listen, help and guide me to complete my work and keep me on the right path. I would also like to thank the department of Petroleum Engineering and Geosciences of Universiti Teknologi PETRONAS (UTP) and the coordinators of Final Year Project 1 and Final Year Project 2 in providing information and guidelines to ensure this project is completed in time.

Finally, sincere thanks to my parents, family, and friends for giving me support and encouragement throughout completing this project. In shore, I would like to thank everyone who has involved directly or indirectly with me throughout the project period.

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CHAPTER 1

INTRODUCTION

1.1 Background Study

This project is entitled "Validity of Permeability Estimation from Published Correlations", studies the capability of different established correlations by using the same core data. The outcomes of this study are the analyses of empirical models selected and the limitations of it. The main focal point of this study is to identify the published correlations to predict permeability. Since there are many correlations existed, only few will be selected to be used in this study. The selection of the models is based on few criteria needed. On the sideline, this project also studies the factors of inconstant results when data is applied to each correlation. The limitations of each model will be investigate and analyze.

The permeability of a rock is a standout amongst the most crucial parameters used in the estimation of petroleum reservoirs. (Aigbedion, 2007). This is because permeability plays an important role during the progress stage of any reservoir. Permeability is defined as the measurement of a rock's ability to transmit fluids. Permeability is generally measured in darcies or millidarcies unit. Nevertheless, in order to accurate production performance prediction, a exact knowledge of its distribution in the reservoir is very important.

Numbers of methods to measure permeability have been proposed. Studies demonstrate that three major methods that have been used to measured permeability are formation testers, routine core analysis and also well testing. (Ahmed et al., 1991) Permeability prediction is considered as a very crucial and difficult chore in reservoir simulation study. Quantitative determination of permeability is usually very a costly coring programs and also involved the extensive laboratory effort to conduct the measurement under the reservoir conditions.

During the earlier stages of industry, in order to calculate approximately permeability at the wells with no core, simple permeability-porosity changes were produced. Nevertheless, the relationships formed were defective. The results indicated were also not in a decent concurrence with field information. Because of this, a considerable measure of new models has been proposed to foresee penetrability by consolidating with different parameters. Complete discussion of the techniques accessible has been published by Nelson in 1994. He demonstrated that the best models can be portrayed by a straight relationship in the log-log permeability –porosity coordinate structure. (Nelson, 1994)

All this models have different parameters and assumptions used. As example, Timur, Tixier, Coates and Coates & Dumanoir are among the most empirical models that been utilized. (Balan et al., 1995) Based on these four models, only Coates and Dumanoir model does not use this assumption; where they assume certain values for saturation exponent and cementation factor and are applicable to clean sand formations.

Complete evaluation of four permeability models between Windland model, Kozeny-Carment model, Civan model and Lucia model have been done by Haro in 2004. In his studies, he came with a conclusion that the Kozeny-Carmen model is the most reliable model that has great hypothetical bases.(Nooruddin & Hossain, 2011)

1.2 Problem Statement

Oil and gas companies use both accurate and approximate permeability values. Usually the values are compared and correlated without much consideration on how each value was determined. Several important conclusions and decisions about formation flow potential and other aspects of reservoir management and development are based on the comparisons and correlations.

The purpose of this study is to review the commercially available permeability correlations and discuss on the potential of each correlation to match with the core data measurement.

Few problem statements have been recognized to conduct the study of this project;

I. What is the capability of each empirical model with different parameters when tested on the data available?
II. Does all the correlations are suitable for any different kind of properties?
III. Why and how some correlations give different results?
IV. What are the limitations of each correlation have?

1.3 Objectives

The objectives of this project are:

i. To measure up the permeability correlations based on their pore configuration
ii. To identify the validity of the permeability estimation from the published correlations
iii. To discover the limitations of the correlations

All of these objectives are produced and are constrained as indicated by accessible resources.

1.4 Scope of Study

The scope of study for this project can be simplified as below:

i. Empirical Models
ii. Pore configuration

This paper analyzes the existed permeability correlations. Permeability models that are chosen are based on the parameters incorporating with the permeability and also the assumptions given. Kozeny's model, Carman's model, Sheffield's model, Wyllie's model and also Coates's are among the empirical models that have been used for this study. Study on the effects of permeability on different pore configuration will be emphasizing for this study.

1.5 Relevancy of Project

This project is relevant to be use in early development phase of reservoir to predict the permeability relationship. Since different models will be incorporating with different parameters, the results for each correlation are likely to be a little bit different. Hence, this study is pertinent to geologist or reservoir engineers in understanding of the capability of different correlations.

1.6 Feasibility

In order to ensure this project feasibility, timeline for this project is created. The objective and methodology of the project are additionally created to comply with the time allocated within available resources.

CHAPTER 2

LITERATURE REVIEW

2.1 Permeability

Permeability rules the displacement of fluids through the pore space of permeable media. Torskaya states that permeability is a standout amongst the most vital and least predictable transport properties of permeable media in reservoir classification. (Torskaya et al., 2007). Hasan (2011) also agreed that pemeability is one of the most crucial parameters to measure in any reservoir rock. Its significance emerges because of the significant part it plays during the development period of any reservoir.

The common meaning of permeability as illustrated by Darcy is the natural characteristic for a substance that proves how effectively a liquid can flow through it. The standard unit for permeability measurement is Darcy. Darcy's Law is shown as follows;

$$k = \frac{q\mu L}{A\Delta P}$$

Where q is defined as the flow rate, L is for the length, μ is for the viscosity, the cross sectional area is represent as A and lastly ΔP the pressure drop.

Commonly, the structure of the porous medium is the first consideration in order to determine permeability. Due to this, various researcher on the subject of the correlation of the permeable structure and its permeability have been carried out.

2.1.1 Determining Permeability

All permeability qualities are required within the reservoir interim at the wellbore for various functions. In order to develop the completion plans, the dissemination and variety of the permeabilities are required by the engineers. Subsequently, the same data is also required as information to the geocellular model and element –flow count.

Based on Malureanu's study, the estimation done on cores, results of hydrodynamic investigations and also correlations based on relationship between other measureable petro physic properties are the basis for permeability values. Among the properties are irreducible water saturation, porosity, cementation, formation resistivity and others. (Malureanu et al., 2010)

Evaluation of the permeability can be completed using empirical equations if there is no good core data available. Pore size, pore throat geometry and porosity are the aspect that controlled the permeability. However, permeability values that are acquired from the determinations from tests or from hydrodynamic analysis are favoured as opposed to the ones obtain from the correlations, which are considered to be less accurate. This is because the qualities acquired from cores are not precise either.

Nevertheless, despite the fact that it is said to be most correct technique there could be some errors that need to be considering as well when using the permeability determinations from samples. One of the factors can affect the accuracy of the results is the cores does not represent as the whole as it is heterogeneity. Other than that, the samples are selected randomly. Most of the time, the best core will be chosen. During the process of preparation also can affect the cores especially during washing or cutting.

2.2 Porosity

Porosity, permeability and relative hydrocarbon saturation are a part of the regularly utilized parameters as a part of the assessments of petroleum reservoir. According to Craft (1991), the symbol Ø represents the porosity and is characterized as the ratio of void space, total bulk volume of the rock or pore volume. The ratio is expressed in term of either as fractional or in percentage. Normally, fractional is always used as the value of porosity when applying in equation. Similarly, porosity is characterized as the degree of the volume of voids in a rock to the mass volume (Hook, 2003).

While Lucia (1995) classified porosity has been classified as interparticle and vuggy. The interparticle of porosity take account of intergrain and intercrystal porosities and correlates reasonably well with permeability. Lucia desribed porosity as vuggy, which may include separate fractures and vugs which does not correlate with permeability.

Porosity is determined mathematically by the following relationships;

$$\emptyset = \frac{Pore\ Volume}{Bulk\ volume}$$

Theoretically, if Vp = total pore volume, therefore, the porosity is the total porosity. Hence if Vp = effective pore volume, the porosity is the effective porosity. Undoubtedly the effective porosity will relate better with permeability than the total porosity. Nonetheless the contrasts between the total and effective porosities is very small and be neglected.

Other than that, porosity is characterized in two distinct types;

- Effective Porosity
- Absolute Porosity

2.3 Permeability – Porosity Relationship

Porosity and permeability of reservoir can be correlated with the essential rock properties of packing, composition and texture. Numerous of studies have been conducted in order to establish the permeability based on knowing the porosity. Permeability of porous media is typically expressed as capacity of some physical properties of the interconnected pore framework, for example, porosity and tortuosity (Costa, 2006).

Despite the fact that it can be easily be assume that the permeability values are rely on porosity, it is not easy to figure out which the appropriate relationship is. A definite learning of size distribution and spatial arrangement of the pore channels in the porous medium is needed. As example, between two porous systems, the porosity could be the same but not for permeability.

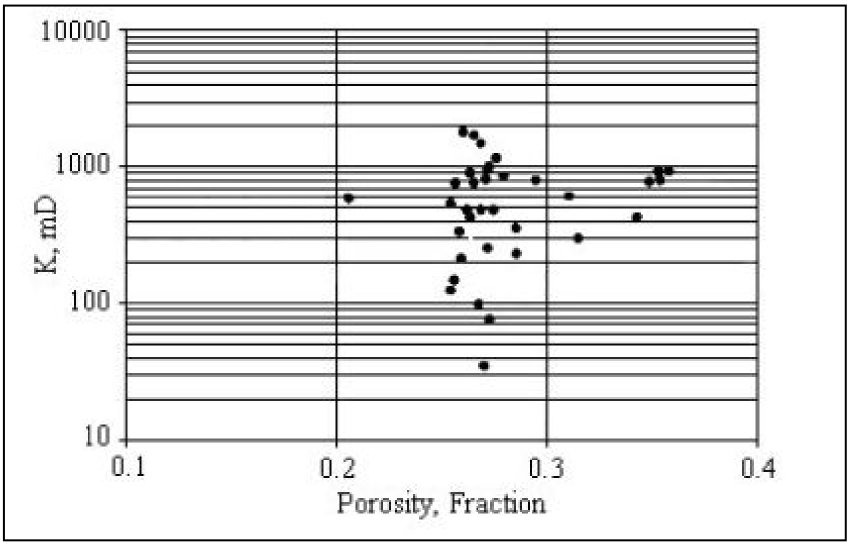

Figure 2.1: The permeability-porosity correlation for even considered and homogenous sandstone. (Malureanu et al., 2010)

In Figure 2.1, the correlations between permeability and porosity can be considered qualitative at most. Other than that, it also shows that the correlation does not direct to create a calculus relation.

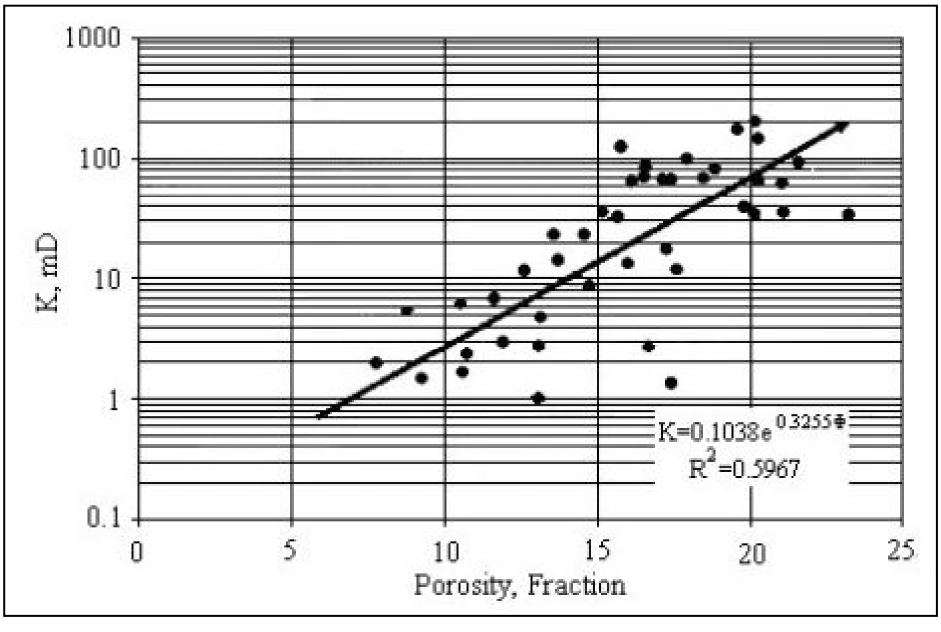

Figure 2.2: The permeability-porosity correlation for even considered and homogenous sandstone. (Malureanu et al., 2010)

On the other hand, Figure 2.2 shows situation for a good permeability-porosity correlations. A quantitative dependence can be recognized. It is believed that good results of permeability-porosity correlation were obtained if the rocks have the same lithology. Chilingarian (1992) has made correlations for different lithology. The correlations are presented as follows;

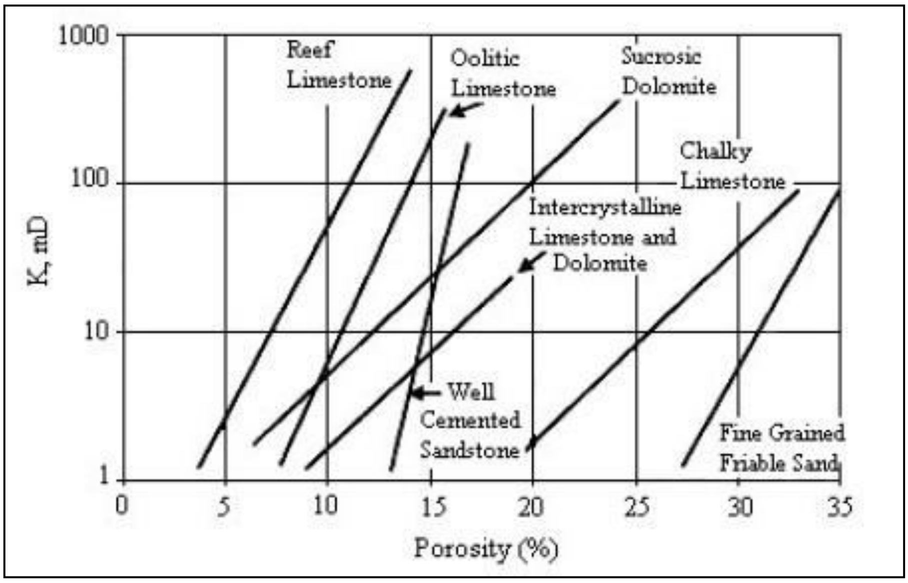

Figure 2.3: The correlations of permeability-porosity for different lithology (Chilingarian, 1992)

2.4 Estimating Permeability

Numerous relationships between permeability and other petrophysical properties have been accounted for. The empirical models have been created for relating the permeability of a permeable medium to its other petro physical properties; grain size, water saturation and others (Timur, 1968). Russel (1989) also mentioned that, there are few numbers of methods for estimating permeability exist. One of the techniques is by utilizing the information on grain size, sorting, porosity, packing and grain shape to predict permeability using empirical relationships. Distributed permeability comparisons in view of petro physical properties are utilized by researchers to predict the permeability. The outcomes on the other hand, are not necessarily can be used to other location. It is subsequently, essential to figure out which permeability equations are suitable to be used.

2.4.1 Permeability relationship based on grain size

Grain size is a basic independent variable controlling permeability in unconsolidated sediments (Graton and Fraser, 1969). The significance of grain size is demonstrated by applying to the essential inherent permeability comparison.

The permeability that varies as the square of grain diameter was presented by Hazen (1892) and Schlichter (1899). This theory has been conduct by other researchers and gives excellent detailed discussions of the derivation and limitations of the relationship and varieties of it.

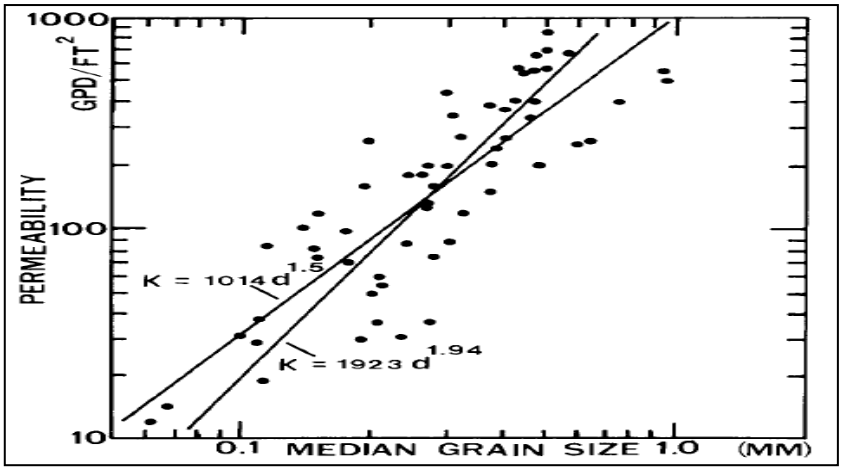

Figure 2.4: Permeability versus grain size for Arkansas River alluvium (Bedinger, 1961)

Figure 2.4 illustrates the plot of permeability versus grain size. This type of plots is described as a common in literature. The parameter dimensionless constant that is used to calculate permeability depending on grain size, is said to be taken to incorporate all components characteristic for the medium that control permeability with the exception of size. According to Krumbein and Monk (1942) and Rose and Smith (1957), sometimes the dimensionless constant can be known in certain circumstances. In such a case, the option to estimate permeability using grain size alone is allowable.

Numerous arrangement of permeability information has been published which are promptly controllable to measurable investigation. For the most part the information utilized are from the early piece of this century, just a percentage of the information as of late acquired exist. Referring to figure 2.4, the information displayed a substantial arrangement of information of reliably got information from one regular habitat covering an extensive variety of size and permeability values. The line Bedinger initially displayed has an incline of 1.94 instead of 2.0 however all the more imperatively the force minimum squares relapsing of the digitized information brought about a slant of just 1.47. Alluding to figure 2.4 and 2.5, it was the different inclines of the two lines fit to the Bedinger information which contrasting the utilitarian relations between grain size and permeability.

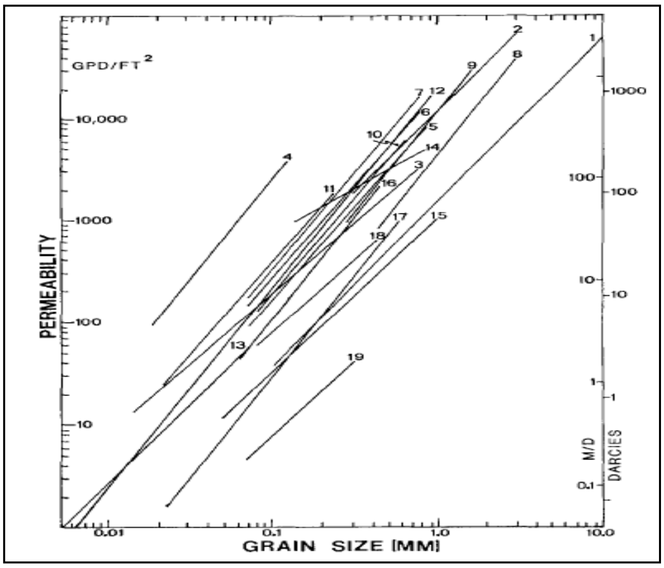

Figure 2.5: Permeability versus grain size for19 sets of data from the literature. Lengths of lines approximate ranges of data (Bedinger, 1961)

Table 2.1: Summary of data and results of Bedinger's study (Bedinger, 1961)

Data source	N	R2	a	b	Comments
1. Hazen	10	.99	1,505	1.60	Filter sands
2. King	10	.99	11,904	1.56	Sands 36-45
3. Stearns	24	.62	4,272	1.33	Assorted samples
4. Schriever	16	.97	208,818	1.94	Glass spheres
5. Hulbert & Feben	8	.99	15,067	1.79	Ottawa sand, 60F
6. Hulbert & Feben	16	.67	10,927	1.81	Sands 9-25, d60
7. Hulbert & Feben	16	.78	24,857	1.88	Sands 9-25, d10
8. Mavis & Wilsey	12	.79	4,558	1.96	River sand
9. Krumbein & Monk	19	.99	1,229	1.96	Outwash fractions
10. Muskat	8	.78	12,396	1.84	Generalized data
11. von Englehardt & Pitter	35	.83	23,821	1.80	Loose to packed sieve fractions
12. Burmister	66	.92	18,355	1.95	All grain sizes
13. Burmister	20	.82	3,235	1.55	Silt only
14. Rose & Smith	14	.72	5,804	1.11	Assorted data
15. Bedinger	59	.67	1,014	1.47	River alluvium
16. Harleman *et al.*	10	.98	128,996	2.05	Uniform sizes
17. Keech & Rosene	42	.90	3,297	1.99	River alluvium
18. Masch & Denny	12	.71	1,873	1.41	River sand fractions

Furthermore, the pore throat size has been mentioned as the prime control of the permeability value. Pore sizes could be determined on when sediment was deposited and the range of its consolidation. Commonly Katz-Thompson equation is being used to calculate pore throat size from permeability and porosity available.

Other than that, Berg's model is consider as a well-known correlations linking petro logical variables which are grain size, sorting and shape to permeability. In his studies, he assumed that there is no change in shape or direction of those pores that break through the solid. A simple relationship was expressed as for permeability are derived from each packing. This resulted on a liner trend of log permeability against log porosity.

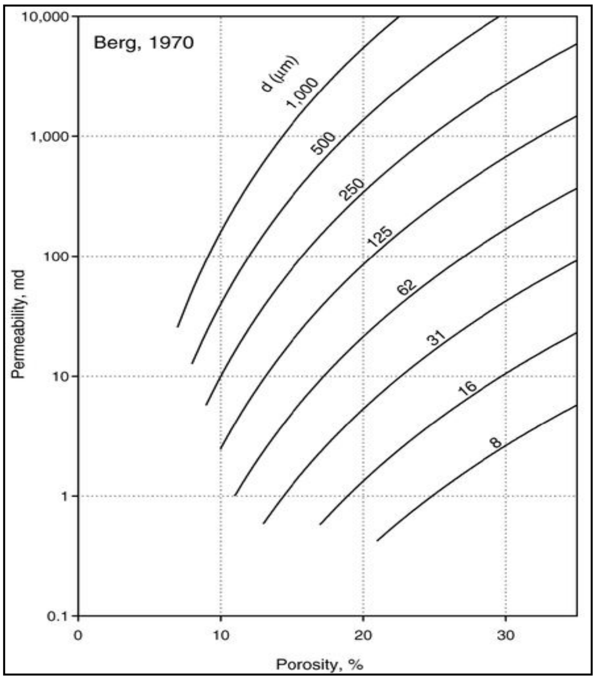

Figure 2.6: Theoretical model by Berg's relating permeability to porosity with varying median grain size

Kozeny model is one of the earliest correlation exist. (Kozeny, 1927). His relationship communicates the permeability as a capacity of tortuosity, effective porosity and specific surface area. The Kozeny's equation was then altered by Carman (1937, 1956) which resulted in becoming the Kozeny-Carman equation. Different attempts were also be made by Hazen (1892), Shepherd (1989), terzaghi and Perk (1964) and Alyamani and Sen (1993). The validity of these formulae relies on upon the sort of soil. In addition, some of these models can give solid estimates of results due to the difficulty of incorporating all potential variables in porous media (Odong, 2007). Other than that, Vukovic and, Soro (1992) mentioned that the application of different empirical models to the same porous medium material can yield different values for permeability.

2.4.2 Permeability relationship based on water saturation

Saturation is defined as a measure of the relative volume of every liquid in the pores. Accordingly, oil saturation is considered as the ratio of the volume of the oil in a permeable rock to the pore volume of the same rock. Commonly, saturation is expressed either in percentage or fractional which ranges approximately from 0 to 100. In the other hand, irreducible water saturation is characterizes as the maximum water saturation that a formation can maintain without producing water. This water, even though it presents, it will not flow due to the capillary forces.

In empirical modelling, the best estimation of porosity and irreducible water saturation is needed in order to predict the permeability. Different researchers have made an establishment of a relationship between permeability, irreducible water saturation and porosity. (Mohaghegh et al., 1995)

According to Timur (1968), another method to establishing a relationship between porosity, permeability and residual water saturation is by taking account the assumption of a straight line relationship. This straight line relationship is between the residual water saturation and the different surface area.

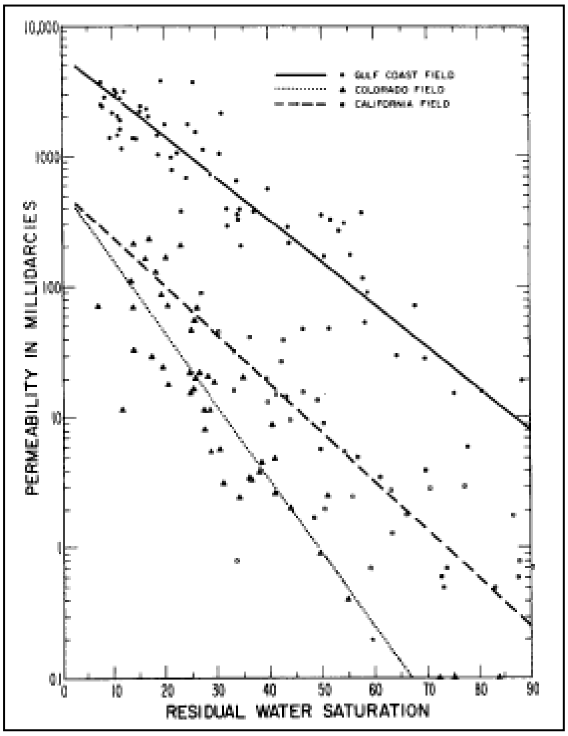

Figure 2.7: Permeability against residual water saturation (Timur, 1968).

Based on the figure 2.7, the data seems scattering all over the plots. This demonstrate that neither porosity nor residual water saturation are agreeable general predictor of permeability.

The general relationship to estimate permeability based on porosity and residual water saturation is as follows;

$$k = 0.136 \frac{\emptyset^{4.4}}{Swi^2}$$

By using the equation, it can accelerate the estimating of permeability, and were plotted in a form of chart similar to the Schlumberger Chart as shown in Figure 2.8 below. The calculated value of porosity and residual water saturation were input into this chart to estimate the permeabilities within the stated limitations of above equation.

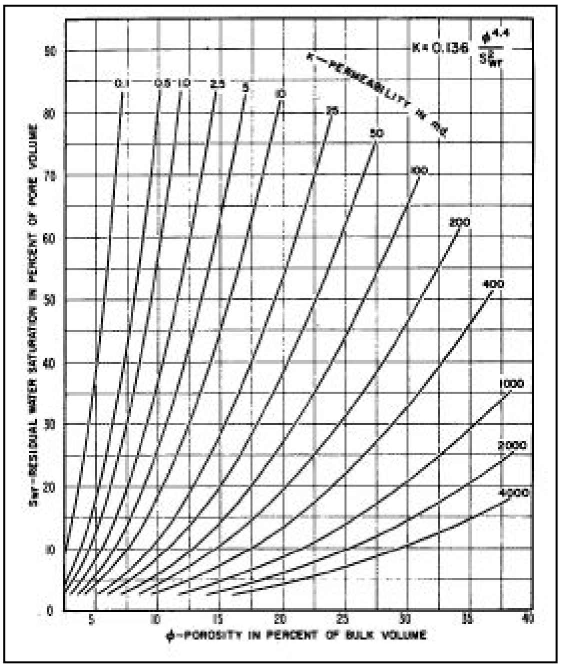

Figure 2.8: Estimating permeability from porosity and residual water saturation (Timur, 1968).

2.4.3 Permeability relationship based on cementation

From Archie's equation, the cementation factor has specific effects depending on the type, shape and size of the grains, size and shape of throats and the size and number of deadlock pores. It is not a constant value but cementation factor is variable relying upon numerous physical parameters and litho logical traits of permeable media.

Cementation factor can indicate the type of porosity. According to the experiments that conducted by Towle (1962) and Lucia (1983), the results showed that as the porosity become more vuggy, the cementation factor will be increasing. Likewise, Aguilera (1974) stated that the cementation factor will be higher when inter-connected porosity exists. When characterizing the cementation factor for shaly formations, interconnected of porosity of micro porous media seems to be more effective. This could probably be explained by the inter-connected porosity works to improve the cementation factorwhere particles get to be closer to one another and pores get to be littler or even shut. (Salem, 1993).

Besides, the ability of the formation to store and transmit the liquids is influenced. Cementation can cause reduces in porosity, and even more drastic in permeability since cement can extensively plug the smaller pore throats which the liquids have to pass through.

CHAPTER 3

METHODOLOGY

3.1 Project Phases and Workflow

This project has been divided into 5 stages. Figure below summarized the stages involved in this project.

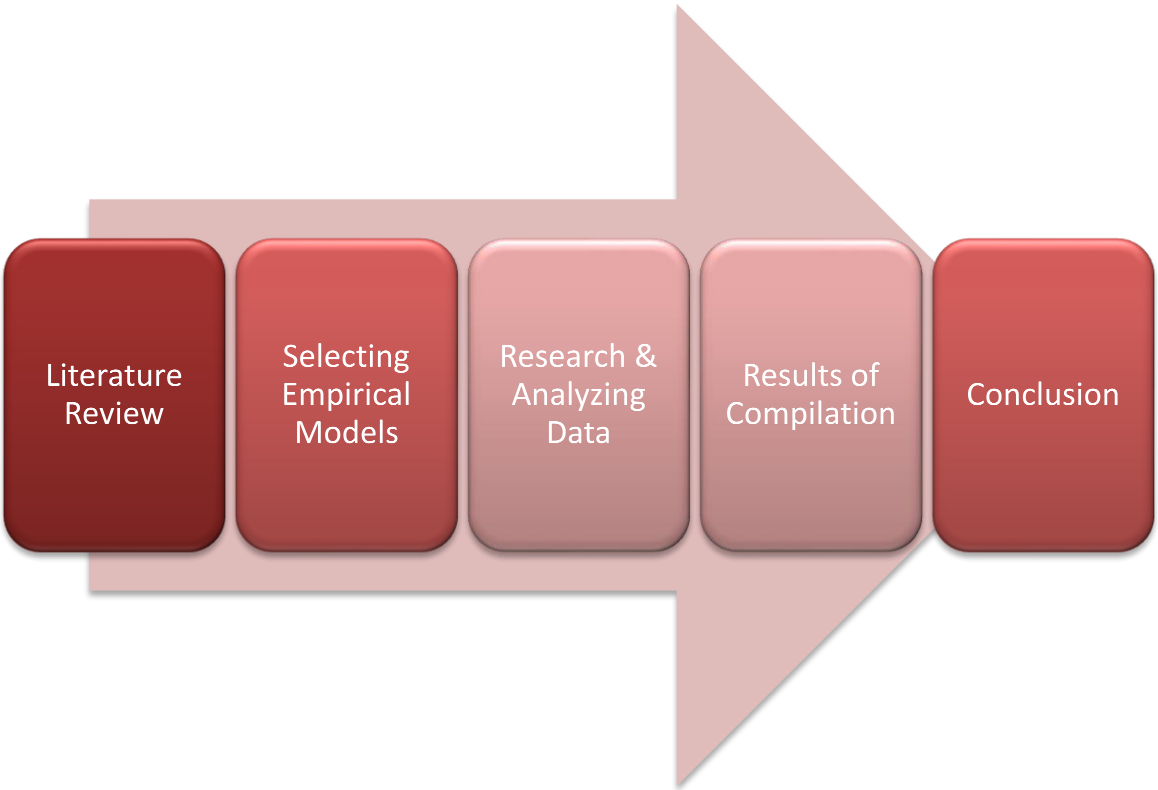

Figure 3.1: Methodology workflow

Stage 1: Literature Review

To address the appropriate correlations among techniques, permeability itself must be defined. Understanding the fundamental of permeability is importantly needed. Studies on previous research and studies are used throughout this study. The characteristics of pore configuration also are important.

Stage 2: Selecting Empirical Models

For the empirical models, correlations that are related to permeability are identified and listed. Parameters of each correlation are also been identified and studied. These parameters would help to give assumptions of the out coming results later. Numerous of the correlations are first identified. Next, few will be selected depending on the parameters and descriptions of the model.

Stage 3: Research and Analyzing Data

A set of data from sandstone reservoir are being used for this study. The classifications of the samples are first being identified. Due to limited sources, not all the parameters related are available. This presented data will be used to all of the empirical models. It will then be analyzed based on the validations of the correlations formed. To understand more about each model's characteristic, continuous research was conducted.

Stage 4: Results of Compilation

Few correlations were formed accordingly. The general trends of the correlations were being identified. The analyses were then made by comparing the results with previous studies. The results then would be compiled and tabulated.

Stage 5: Conclusion

This study would then be concluded as shown in figure 3.2.

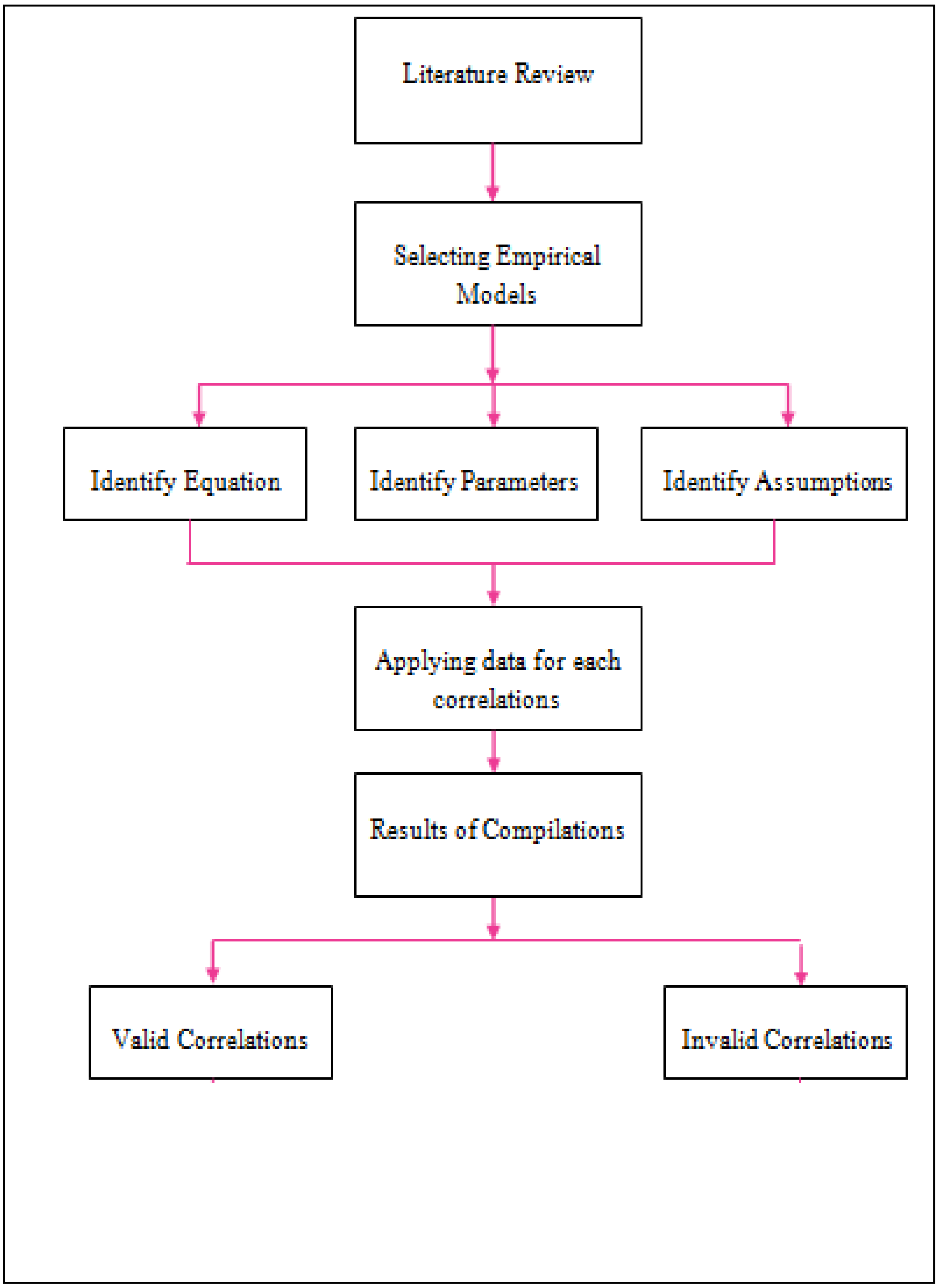

Figure 3.2: Project Workflow

3.2 Gant Chart and Key Milestone

Table 3.1: Project Gant Chart and Key Milestone for FYP 1

Project Activities	Weeks No													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Literature Review														
Preliminary Research Work														
Identify Correlations														
Collecting Core Data														
Core Data Measurement														

Table 3.2: FYP 1 Gant Chart and Key Milestone

Project Activities	Weeks No													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of Project Topic														
Preliminary Research Work														
Submission of Extended Proposal														
Proposal Defence														
Project work Continues														
Submission of Interim Draft Report														
Submission of Interim Report														

Suggested milestone

Table 3.3: Project Gant Chart and Key Milestone for FYP 2

Project Activities	Weeks No													
	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Literature Review														
Analyze Data with Different Correlations														
Verify the Validity of Permeability														

Table 3.4: FYP 2 Gant Chart and Key Milestone

Project Activities	Weeks No													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Project Work Continues														
Submission of Progress Report														
Project Work Continues														
Pre-SEDEX														
Submission of Draft Final Report														
Submission of Technical Paper														
Viva														
Submission of Project Dissertation (Hard Bound)														

Suggested milestone

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this part, the proposed methodology is being presented for analysis and acceptance of results. To test the validity permeability estimation from existing correlations, 9 samples were obtained from sandstone reservoir. Data obtained have been applied on existing permeability correlations based on pore configuration, water saturation and cementation distribution.

4.1.1 Data Analysis

A total of nine (9) samples were use throughout the project. Data of porosity, measure permeability, water saturation, fineness, sorting and cementation also are available. Classifications of sorting are based on the calculation using standard deviation formula. Meanwhile, the qualitative evaluations of cementation were recorded in the field.

Table 4.1: Data available for 9 samples of sandstone formation

Sample ID	Porosity %	Water Saturation (%)	Fineness	Sorting (mm)	Cementatio n	Grain size diameter (mm)
1	31.4	40.4	Fine	Very poor sorted	2.06	0.42
2	33.4	18.5	Fine	Moderately sorted	2.05	0.35
3	32.8	15.1	Very Fine	poorly sorted	1.84	0.25
4	31.1	22.7	Very Fine	Well sorted	1.89	0.08
5	30.2	16.4	Medium	Well sorted	1.93	0.074
6	13.8	63.7	Fine	Poorly sorted	1.91	0.297
7	13.9	54.2	Fine	Well sorted	1.93	0.62
8	12	59.8	Medium	moderately sorted	1.73	0.312
9	12.3	67.7	Fine	Poorly sorted	1.81	0.21

There is no reasonable relationship between permeability and porosity with the pore formation characteristics. Nelson (1994) stated that in sandstones, an increment in rock and coarse grain size substance can caused permeability to build even while decreasing. He added more, in order to calculate permeability from porosity and other measurable rock parameters fall into three categories depending on surface are, pore dimension or grain considerations.

4.2 Permeability, porosity and cementation

There is poor connection between permeability and porosity among the samples observed in this research. Analysis of sample data shows that the sorting, level of cementation and packing impacts the relationship between permeability and porosity. Based on figure 4.1, the distribution of relationship permeability and porosity are scattered. The correlations above can be explained because of the permeability is not influenced only by porosity but also by others factor. These varieties are recognized to contrasts cementation, grain size, and sorting and pore geometry. Furthermore, samples with low porosity and high permeability values tend to be coarse and poorly sorted. Meanwhile, in figure 4.2 below, it can be seen the relationship between permeability and cementation of the samples, where the permeability declines with higher value of cementation.

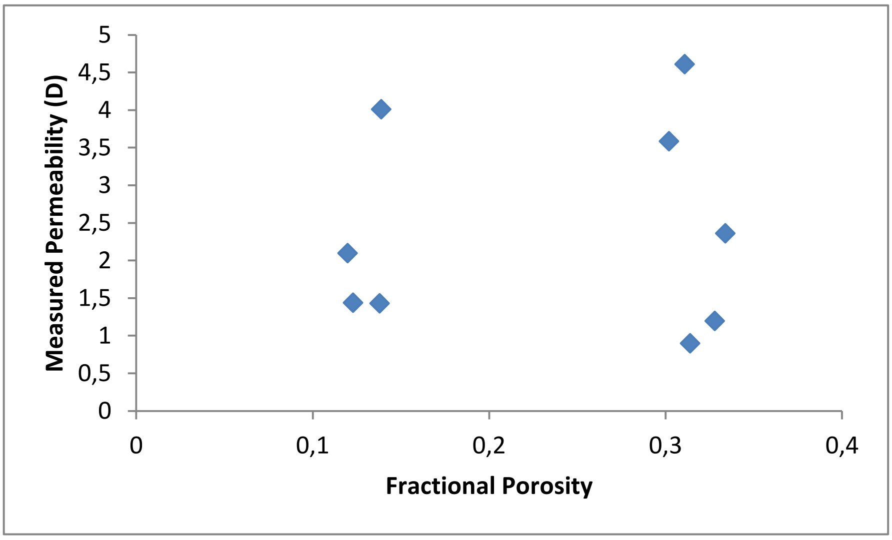

Figure 4.1: The permeability & porosity distribution of data for this study

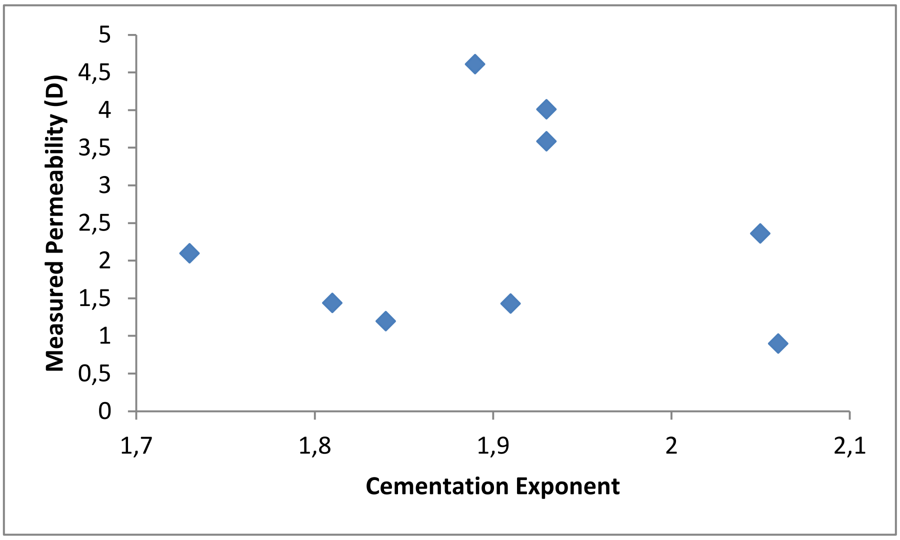

Figure 4.2: Influence of cementation on permeability

4.3 Selecting appropriate correlations

Published permeability relationship in view of porosity, grain size, water saturation, and rock type and cementation appropriation of sandy residue are used by researchers to predict the permeability of the well core. The equations however are not always practicable from one site to another. Hence, it is very crucial to figure out which permeability relationships are suitable to be used in different conditions. In this study measured permeability was evaluated with permeability values obtained from various ordinarily utilized permeability correlations.

4.3.1 Correlations based on water saturation and surface area

A common relationship proposed by Wyllie and Rose (1950), relates the permeability to the irreducible water saturation and porosity. The relationship is shown as follows;

$$k = \frac{a\emptyset^b}{{S_{wir}}^c}$$

Where parameters a, b and c are measurably determined model parameters. Relying on this equation, a lot of new empirical models have been proposed to estimate permeability depending on the values of porosity and irreducible water immersion got from well logs.

In view of the fact that permeability relies on the influence of porosity and also the inverse square of surface area, then permeability can be calculated by assuming that residual water saturation (Swir) is corresponding to particular surface area. In 1977, Granberry and Keelan issued a set of graphs describing porosity, permeability and water saturation for Gulf Coast Tertiary sands that regularly are poorly consolidated. The correlations were initially presented critical water saturation (Swic) as a function of permeability with porosity as a factor.

The Wyllie-Rose equation to determine permeability on the premise of porosity and saturation in irreducible water represents to a non-direct model in a, b, c parameters. Based on the study done by Malureanu (2010), the a, b, and c parameters were already calculated for different litho logy including sandstone. The relation for sandstone is shown as follows;

$$k^{\frac{1}{2}} = 2.08 \frac{\emptyset^{1.34}}{S_{wirr}{}^{2.55}}$$

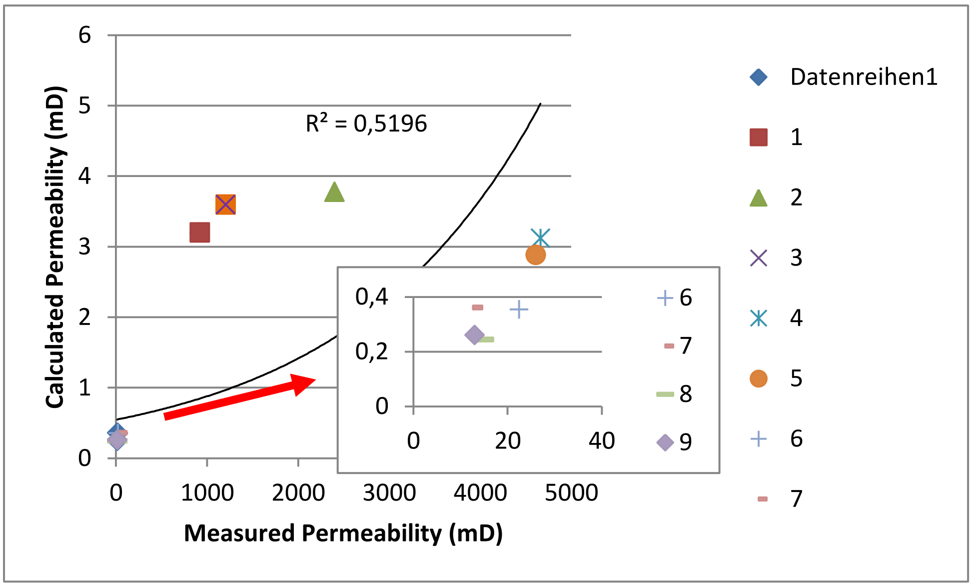

Figure 4.3: The permeability distribution for Wyllie-Rose correlation

A non-linear model of Wyllie-Rose's was obtained. Figure 4.3 shows that there is differences between well sorted and poor sorted in the plots. The higher value permeability seems to be a well sorted characteristic. Exception for two of the samples where even though having poor sorted sand, the calculated permeability value is still higher. Furthermore, when comparing to Timur's correlation, Wyllie-Rose's correlation give lower estimate value. The generally view is that any relation that has this form is not generally valid but very good results for the collector for which it has been established can be obtained.

In 1974, an empirical permeability technique has been improved. The equation was proposed by Coates.

$$k^{\frac{1}{2}} = 100\frac{\emptyset^2(1 - S_{wir})}{S_{wir}}$$

K is known to be in milidarcies. This equation likewise has fulfils the state of zero permeability at zero porosity and when $S_{wirr} = 100\%$. Coates and Dumanoir abridge the past proposed equations and still fulfilled the zero permeability condition. Nevertheless, the formation has to be at irreducible water saturation.

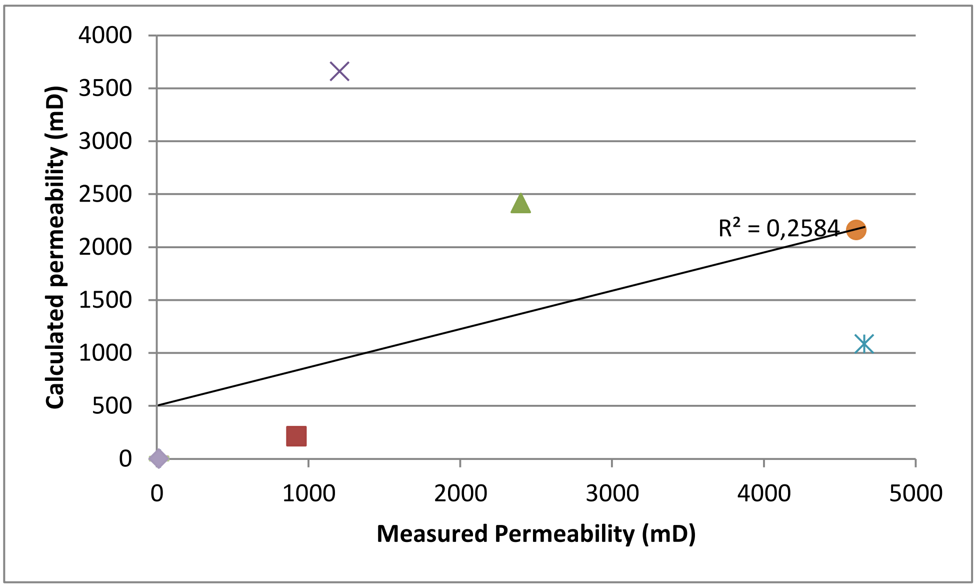

Figure 4.4: Comparison of measure and calculated permeability for Coates' correlation

Other than Wyllie-Rose, one of the most common used empirical models is TImur's correlations. He used a set of data consist of 155 sandstones samples from three different oil fields. The three set of samples of sandstones displayed different level of sorting, consolidation and series of porosity. Timur measure initial water saturation (Swi) using centrifuge and the relationship or permeability is expressed as follows;

$$k = 8.58102 \frac{\emptyset^{4.4}}{{S_{wir}}^{2}}$$

However, there was no hypothetical source for the substitution of Swi for specific surface area as Timur did.

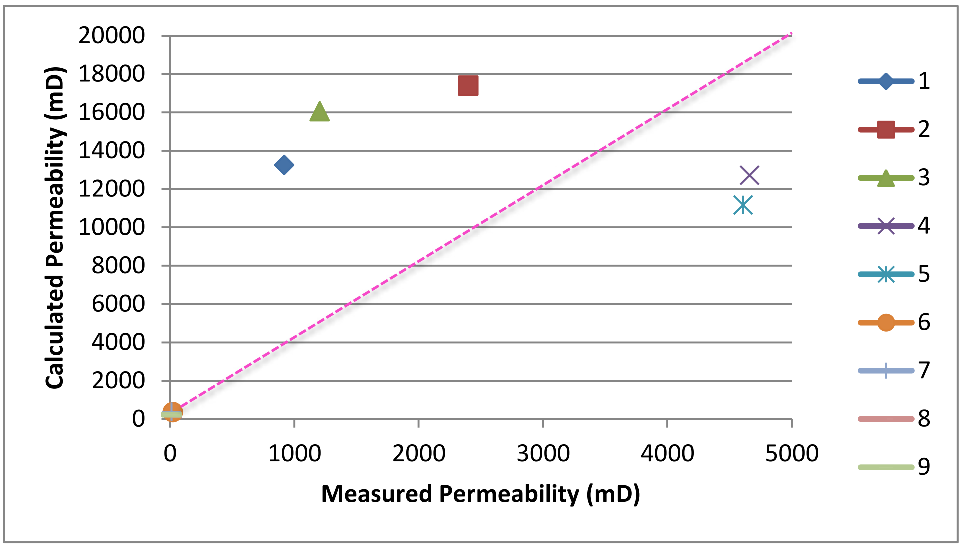

Figure 4.5: Comparison of measure and calculated permeability for TImur's correlation

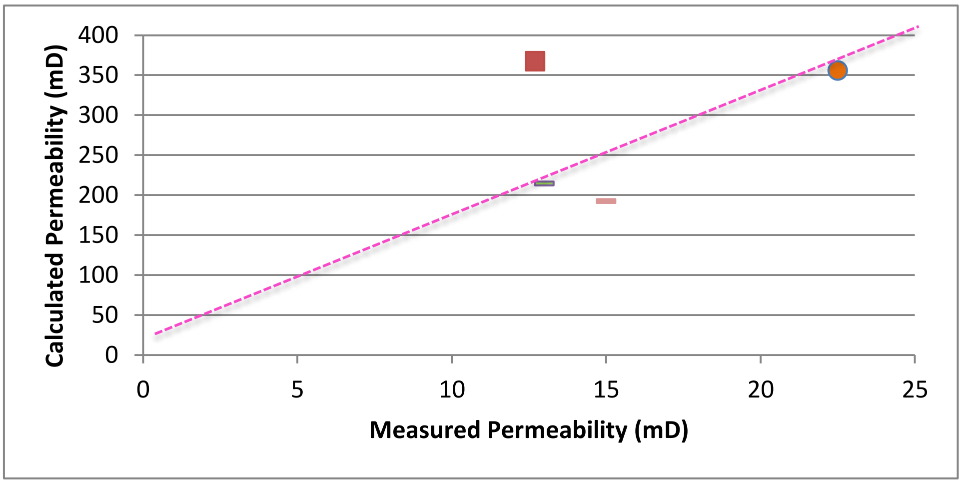

Figure 4.6: Timur's correlation in smaller range

As can be seen in the figure 4.5, only two samples are giving good results of permeability for poorly sorted sample. Next sample which is close to the line is sampling no 8. This sample is described as moderately sorted. However, only these three samples are giving good results while the rest are not match with the measured permeability.

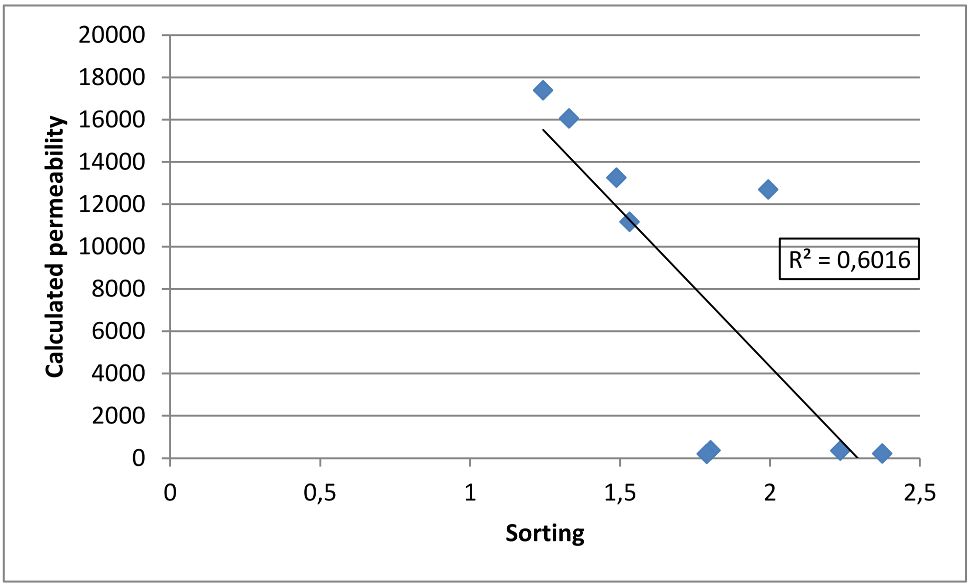

Figure 4.7: Calculated permeability versus degree of sorting for Timur's correlation

A graph of sorting versus calculated permeability is plotted to see the relationship between Timur's correlation and sorting. The R-squared value obtained shows that the graph is good correlated. The sorting values were measured based on the standard deviation equation. The results are display as in Figure 4.7. It can be seen that for higher values of sorting, indicates that the sand is more poorly sorted. Sample 9 and sample 6 shows identical results with previous correlations for estimating permeability of poorly sorted.

On the other hand, Coates (1981) proposed a relationship for permeability determination. This mathematical statement was then later used by Schlumberger (1988) and Ahmed (1989) and produced an algorithm as follows;

$$k = \left(\frac{100\phi_e^2(1 - S_{wi})}{S_{wi}}\right)^2$$

This correlations guarantees that permeability decreases to 0 as Swi increments to fill the whole pore space.

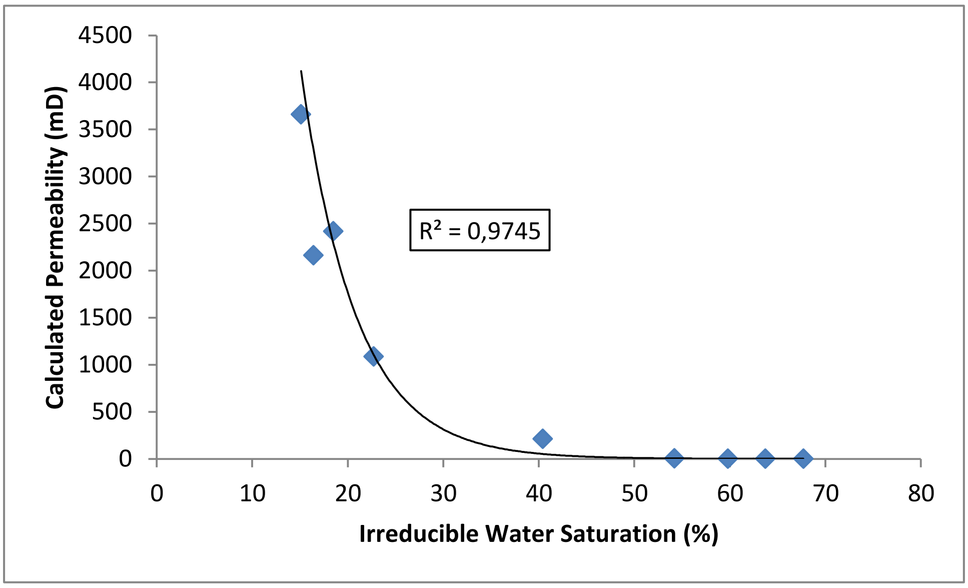

Figure 4.8: Plot between calculated permeability versus water saturation

Referring to the figure above, it illustrates the variations of the calculated permeability for different values of irreducible water saturation from all samples. Torskaya stated that, rock permeability declines with increasing estimations of irreducible water saturation, all specimens show a comparative pattern of decreasing permeability**.**

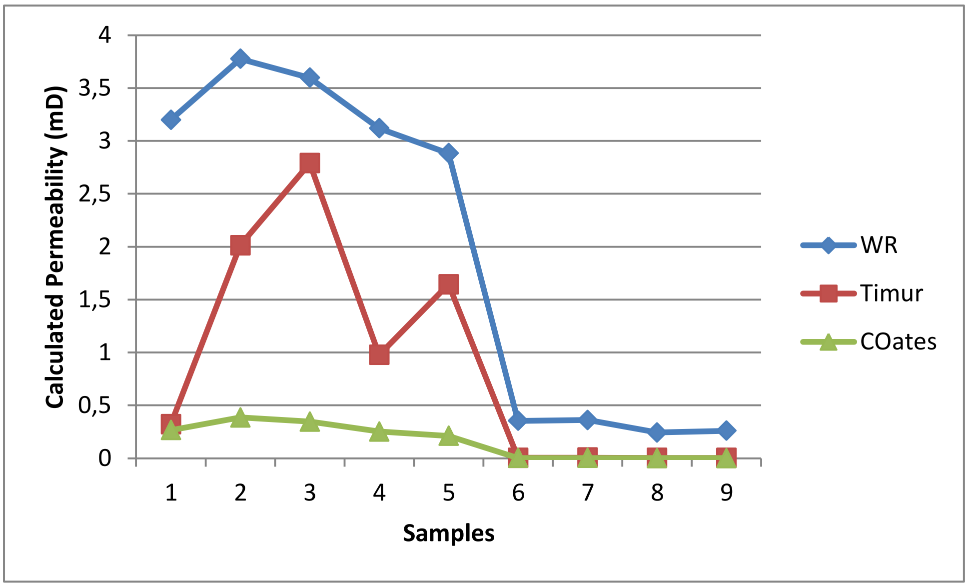

Figure 4.9: The value of permeability for all models

Figure 4.9 shows the three different correlations. As can be seen in figure above, Wyllie-Rose's model gives higher permeability value compared to other models.

4.3.2 Correlations based on pore size and grain size

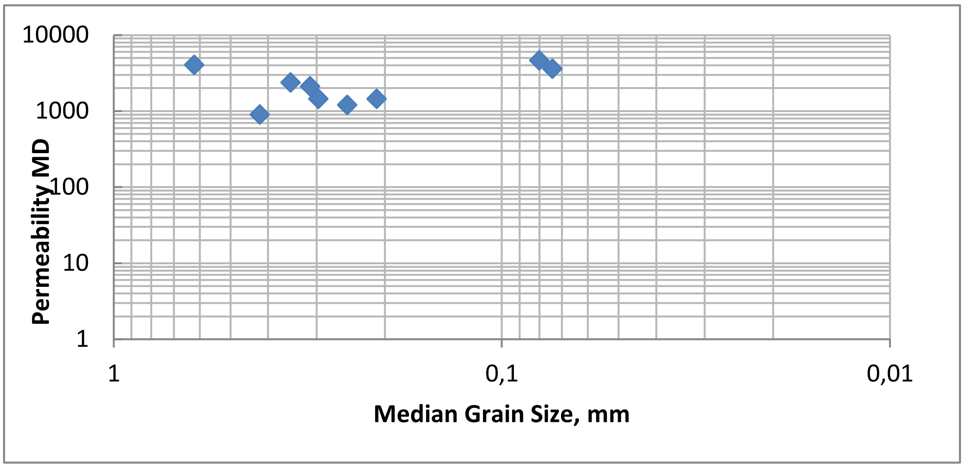

Figure 4.10: Permeability versus grain size from data available

From the plot above, it can be seen that the plots are scattering. This can be assuming possibly the samples' configurations are different from one another. Besides, the plot displayed is more than one log cycle.

Krumbein and Monk (1943), Berg (1970) and Van Baaren (1979) are among the models that were based on the grain size and pore size.

In Krumbein and Monk (1943) studies, they calculated the permeability in sand pack having 40% of porosity at specified size and sorting ranges. The results of their studies combining with the dimensional analysis of the permeability formed the relationship as follows;

$$k = 760D_g^2 e^{-1.31_{\sigma D}}$$

Where $\sigma_D$the standard deviation of diameter and D_g is expressed as the geometric diameter in millimetres. While in Van Baaren's model, he utilized an arrangement of test estimations of porosity, permeability and mercury injection. This model involved the relationship between pore diameter at 70% wetting saturation, grain size and the sorting ranges.

Berg (1970) came out with a model which links the petrologic variables grain sizes, sorting, shape to permeability.

Straightforward relationships for permeability were derived from every packing and construct a straight pattern when log permeability plotted against log porosity. Based in the geometrical consideration the relationships are expressed as follows;

$$k = 80.8\emptyset^{5.1}D^{2}e^{-1385p}$$

Where diameter is in micrometers, permeability is expressed in millidarcies, and porosity is in fractional values. He expressed the above comparison for a scale of grain sizes; increasing in porosity will makes increments in permeability more rapidly. The curves will migrate downward and to the right with declining grain size.

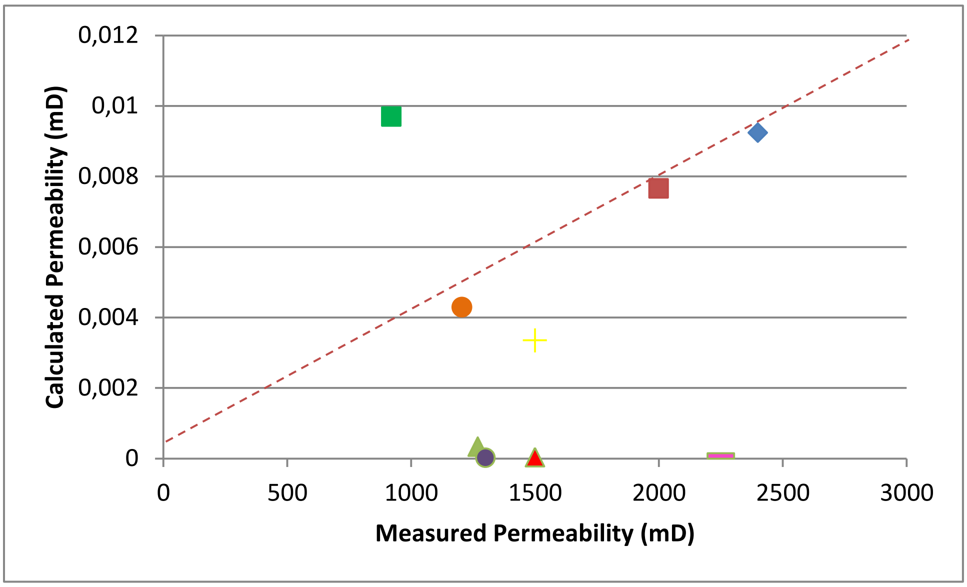

Figure 4.11: Comparison of measure and calculated permeability for Berg's correlation

Figure above was plotted using the Berg's correlation. Three out of nine samples give slightly accurate plotting. These samples are the well sorted samples. The remaining samples show that bad match of the correlations as most of them were classified as poorly sorted. Therefore, Berg's correlation is said give considerable results when being compared with measured permeability.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

1. Correlations between permeability and porosity are observed but they are strongly dependent on pore structures.
2. The accuracy of calculated permeability can be improved if appropriate or sufficient data are obtained.
3. Timur's correlation shows that residual water saturation as a good predictor of permeability for the poorly consolidated sandstones.
4. The results of Coates' correlation also give a good estimate. It was proved that as the irreducible water saturation increase, the permeability decreases.
5. When comparing between three different models, Wylllie-Rose give higher value of calculated permeability. It can be concluded that perhaps the data samples available is more suitable with this correlation.

In future, as a recommendation the study scope could be expanded to include more parameters such as grain sorting factor. Other than that, could also add more different set of data for example sample data from sand formation or carbonate formation.

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