Correlation between shear strength at plastic limit and liquid limit

Incorporating electrical resistivity

By

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15802

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Civil)

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CERTIFICATION OF APPROVAL

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Approved by,

Dr. Syed Baharom

(Name of Main Supervisor)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2014

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 people.

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Moyou Jermalili Roman

ABSTRACT

The samples obtained from a site investigation are often disturbed. A condition that result in false lab results, which underestimate the real value. A correlation provide a lower bound against which the results obtained from lab tests can be compared. This is useful in offsite site investigation where obtaining high quality samples are expensive and difficult to acquire.

The objective of this study is finding the relationship between shear strength at plastic limit (PL) and liquid limit (LL), and to understand the behaviour of electrical resistivity with other properties such as; PL, LL, particle size distribution (PSD) represented as sand percentage in the sample, and shear strength (Cu).

To find the correlation required the shear strength at plastic limit was measured using vane shear test. Liquid limit and plastic limit was measured using cone penetration test and thread rolling method respectively. The PL and LL were represented as a percentage of the mass of moisture over the mass of solid. Moreover, the electrical resistivity was measured theoretically by obtaining resistance. Finally, the particle size distribution was measured using the hydrometer test and determined by the particle size distribution of sample sizes above and below 63µ.

ACKNOWLEDGMET

I am using this opportunity to express my gratitude to everyone who supported me throughout the course of this final year project. I am thankful for their aspiring guidance, invaluably constructive criticism and friendly advice during the project work. I am sincerely grateful to them for sharing their truthful and illuminating views on a number of issues related to the project.

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Thank you,

Moyou Jermalili Roman

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1. INTRODUCTION

1.1.Background of study

Shear strength of a soil is its internal resistance per unit area, to failure along any plane inside it. Soil stability problems such as slope stability, lateral pressure on earth-retaining structures, and bearing capacity, all arise from low shear strength of the soil, thus it is critical to determine the shear strength. It's also important in the design of pile foundation, studies of submarine soils and glacial soils, and offshore foundation designs (Bozozuk,1972; kvalstad et al.,2005; Yafrate and Dejong,2005; Kaybali and Tufenkci, 2010).

Liquid Limit (LL) is the moisture content at the point of transition from plastic to liquid state, whereas the Plastic Limit (PL) is the moisture at the point of transition from semi solid to plastic state or the moisture content in percent, at which the soil crumbles, when rolled into threads of 4.2 mm (1/8 in.) in diameter. These parameters are known as Atterberg limits.

There has been many researches and studies, which suggest a correlation between the Atterberg limits, considering that the soil assumes a specific shear strength at the liquid limit and plastic limits and suggest that there is a definite relationship between them. The initial studies (Wroth and Wood 1978) suggested that shear strength at the plastic limit is 100 times that at the liquid limit. Many studies have been conducted ever since then to verify the validity of this assumption using different type of PL and LL tests and regression methods.

Electrical resistivity (ER) of a soil is the measure of its resistance to the passage of current through it. It's measured by using a wenner electrode or Disc electro method to determine thermal resistivity of soil, hydraulic conductivity of compacted clay layers, and chemical weathering index (CWI) (Y. Ezrin, et al, 2010; Sreedeep et al,2005; Abu-Hassanein et al, 1996; McCarter,1984). Geophysical methods such as electrical resistivity are cost effective, fast, and non-destructive. They are used to discover the site properties without soil disturbance.

Some studies have been conducted to correlate electrical resistivity with various geotechnical parameters of soil such as; water content, shear strength, plasticity index, Standard Penetration Test (SPT), Cone Penetration Test (CPT). Those studies showed a good correlation between Electrical Resistivity and water content (Cosenza, et al, 2006;Ozcep et al,2009; Kalinski and Kelly,1993, etc) . Sudha, et al, (2009) research showed that when the grain size is small (<0.075mm) such as in clay, the electrical current will easily flow through the pore fluid making it less resistive, as the grain size increases, so does the resistance.

1.2.Problem Statement

Laboratory tests are an ideal method of measuring the soil engineering properties. However, soil samples are often obtained in a disturbed condition. A condition that present results different from the natural condition of the soil, and often inaccurate.

Establishing a correlation between the various engineering properties of the soil will provide us with a benchmark or a lower bound against which the results obtained from the lab tests can be compared.

The correlation have a specific and practical application to offshore site investigation, where good quality samples and test results are very expensive and difficult to obtain. In addition, the correlation suggests whether a soil have some strange properties that should be further investigated

1.3.Objective

This project main purpose is:

1. To find the relationship between shear strength at PL and LL for the soil under study.
2. To understand the behaviour of electrical resistivity of the soil under study with some of the soil geotechnical parameters measured during the test; which are; PL, LL, particle size distribution (PSD) represented as sand percentage in the sample, and shear strength (C_u).

1.4.Scope of study

This research uses soil of different types, not only clay. They are remoulded for the tests undertaken. The focus of the study is to correlate the shear strength at plastic limit and liquid limit. Electrical resistivity and PSD are additional findings that were included to widen the study scope.

It does not attempt to find a universal correlation factor for all soils but to find the correlation factor for this soil, compare it with other studies findings, investigate the reasons of variation, and suggest improvements. It also include the correlation of shear strength and PL and LL. A relationship that was not developed before by any study.

This research has some unavoidable limitations such as:

1. Sample size: the number of samples for this study is 10 samples. The small amount of the samples makes the result inconclusive and indecisive. However, it will clarify impact of the mineral and soil composition on shear strength and electrical resistivity.
2. Geographic location: the site from which the samples were obtained will dictate the type and composition of the samples. This might make some of our results site-specific and cannot be generalize for all geographical locations.
3. Variables: variables are parameters in the study that affect the accuracy of the result obtained such as:
    a. Difference in the electrical resistivity due to change in saturations conditions, temperature difference and overburden pressure. This indicate that since this study temperature, and water content are different, the results may or may not match the previous studies result.
    b. Difference of the shear strength at Liquid Limit according to the apparatus used: the results of the shear strength at liquid limit depends on the apparatus, and standard used. The results obtained from a vane shear test at liquid limit varied according to the standards where the one that satisfied the British standard at that time (0.8-1.6 kN/m^2) was higher than that manufactured according to the American standard (ASTM) (1.1-2.3 kN/m^2). Whereas the results obtained from Casagrande apparatus were between 1-3 kN/m^2. Consequently, the results has to be apparatus-specific and cannot be generalize for all apparatus. Nonetheless, the determination of which one is correct or more accurate is difficult. Thus, to minimize the probability of obtaining different result, the same apparatus used in previous studies will be used.

c. Apparatus and Human or experimental error: the apparatus errors are a result of manufacturing errors that can be avoided. On the other hand, experimental errors are a result of human imperfect technique or reading error or a calibration error. During this study human errors will be reduced as much as possible and if committed it'll be recorded, as for the apparatus errors it'll be calculated for each apparatus and summed for all apparatus as follow :

   Apparatus error= 100 x margin of error *(Eq. 1)*

   Experimental error = [100 x (real answer – experiment answer)]/ real answer *(Eq. 2)*

   If experimental error is smaller than apparatus error, then the result is accurate. However, if experimental error is larger than apparatus error, then the result is inaccurate.

d. Limited research references: There is a limit to the number of researches that can be found online or offline thus our scope of study is narrowed to the ones found only.

2. LITERATURE REVIEW

2.1.Correlation of shear strength at PL and LL

The Atterberg limit originally divides the behaviour of clay into two unique states depending on the water content. Thus the liquid limit can be defined as the state at the water content below which it would not flow as a liquid; and plastic limit as the water content below which it could not be rolled into a thread. Many researches have been conducted to correlate PL, LL, and plasticity index with other soil properties (Skempton,1944; Bjerrum and Simons,1960; Seed et al 1964a,b). There has also been attempts to correlate the Atterberg limits to specific values of mean effective stresses and imply a constant ratio between this stresses (Casgrande,1958; Youssef et al,1965; Schofied and Wroth ,1968; Livenh et al,1970; Russel and Mickle,1970).

The shear strength of a soil is one of the main properties that are investigated during site investigation and sample testing because it is crucial to the stability of the structure to be built. However, there is a common belief that the shear strength should be the same for all soils at plastic and liquid limit for clay (Fine-grain) soils at remoulded state (Campbell,1976; Nagaraj and Jayadeva,1983).

2.1.1. Wroth and Wood (1978)

The shear strength can be measured directly or indirectly using many apparatus, which result in various strength values depending on the conditions created or imposed by the type of test. Thus, to obtain a consistent and adequate correlation, only one type of test should be used.

Wood and Wroth (1978), the pioneers in the correlation of shear strength with Atterberg limit took this factor into consideration and as a result, standardized one test which is the triaxial undrained compressive shear strength to develop the relationship. They used the results obtained by Youssef et al (1965), where the shear strength range on large number of remolded clays using the vane shear test at liquid limit was 2.4-1.3 kN/m^2 with a mean of

1.7 kN/m^2. They assumed the equality of the shear strength measured by the vane test and triaixial compression, which resulted in the best estimate of undrained shear strength to be 1.7 kN/m^2.

Results obtained showed a range of strength of 0.7-1.7 kN/m^2, when measured using vane test on four soils with entirely different plasticity index, shown in Fig.1 (Skempton and Northey,1953). Based from the evidence shown in Fig.1, it was assumed that the shear strength at the plastic limit is 100 times that at the liquid limit. And as a result, the best estimate for the plastic limit was 170 kN/m^2.

Through various calculations and assumptions, this equation was produced:

$$c_u = 170 \exp(-4.6\, LI)\ kN/m^2 \qquad (Eq.\ 3)$$

When represented as variation of shear strength with liquid limit

$$c_u = 100\, c_{LL} \exp(-4.6\, LI)\ kN/m^2 \qquad (Eq.\ 4)$$

Where c_{LL} is the undrained shear strength at LL accoding to Youssef et al (1965). Eq. (15) is sensitive to any error in determining the LI, shown by differentiating eq. (15)

$$\delta c_u / c_u = -4.6\, \delta (LI) \qquad (Eq.\ 5)$$

This shows that an error of 0.1 in the LI can result in an error of 46% when estimating c_u. However, the chances of occurrence of such a large error is slim.

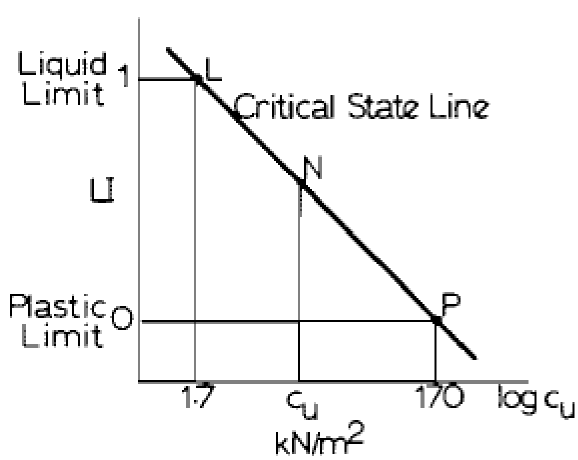

Figure 1: Idealized Relationship between Liquidity index and Shear Strength

2.1.2. Comparison of Different Studies to Wood & Wroth (1978)

Table 1: Comparison of Different studies to Wood & Wroth (1978)

Study	Soil Type	Test Used	Sample size	Results
Worth and Wood (1978)	Remoulded clay	C_u = Vane shear test	Large number Above 100 samples	$C_{u\,LL} = 1.7\ kN/m^2$ $C_{u\,PL} = 170\ kN/m^2$
Kayabali (2011)	Fine grained soils (silt, clay) from lacustrine formation	P_{LL} and P_{PL} = Extrusion From math eq.	120 samples	$P_{LL} = 20$ kPa $P_{PL} = 20{,}000$ kPa
Sharma and Bora (2013)	inorganic soil	$C_{u\,LL}$ = Fall cone test $C_{u\,PL}$ = Thread rolling method	55 samples	$C_{u\,LL}$ line lie close to a line corresponding to $C_{u\,LL} = 1.7\ kN/m^2$ $C_{u\,PL}$ line lie close to a line corresponding to $C_{u\,PL} = 170\ kN/m^2$
		$C_{u\,LL}$ and $C_{u\,PL}$ = unconfined compression test	17 samples	$C_{u\,LL}$ line lie close to a line corresponding to $C_{u\,LL} = 1.7\ kN/m^2$ $C_{u\,PL}$ line lie close to a line corresponding to $C_{u\,PL} = 170\ kN/m^2$

	Bentonite *W*= 210% - 460%	$C_{u\ LL}$ = Casagrande $C_{u\ PL}$ = Thread rolling method	3 samples 6 samples	$C_{u\ LL}$ line lie close to a line corresponding to $C_{u\ LL}$ = 1.7 kN/m^2 $C_{u\ PL}$ line lie close to a line corresponding to $C_{u\ PL}$ = 170 kN/m^2
Study	Soil Type	Test Used	Sample size	Results
Wasti and Bezirci (1986)	15 natural soil 10 artificial soil (natural soil+ bentonite)	C_u = VST PL and LL = Casagrande PL and LL = fall cone tests	25 samples	$C_{u\ LL}$ = 2.15 kPa $C_{u\ PL}$ = 180 kPa R_s = 83 $C_{u\ LL}$ = 2.2 kPa $C_{u\ PL}$ = 208 kPa R_s = 95
O'kelly (2013)	14 mineral fine grain 4 dredge sediment (2 are bentonite)	C_u = VST PL and LL = Casagrande	18 samples	$C_{u\ LL}$ = 1.15 kPa $C_{u\ PL}$ = 82 kPa R_s = 71 $C_{u\ LL}$ = 0.93 kPa $C_{u\ PL}$ = 17 kPa R_s = 18
Kayabali and Tufencki (2010)	Inorganic fine grain	$C_{u\ LL}$ and $C_{u\ PL}$ = Extrusion $C_{u\ LL}$ and $C_{u\ PL}$ = VST	30 samples	$C_{u\ LL}$ = 2.3 kPa $C_{u\ PL}$ = 180 kPa Rs= 78 $C_{u\ LL}$ = 5 kPa $C_{u\ PL}$ = 180 kPa Rs= 36

2.1.3. Analysis of the shear strength correlation studies

The study of Wood and Wroth (1978) was used as the reference against which other studies were compared according to the soil type, test used, sample number, and results. The aim of this comparison is to identify the factors that may have affected the results of the studies and utilize this information to produce similar results to the theory as much as possible.

The repetitive patterns observed in the comparison is that VST and Extrusion methods produce the same result as Wood and Worth's due to higher sample number (>120), fine grains soil such as clay or silt, and no inorganic or artificial constitute.

It can be explained as follow:

1. The higher number of samples increase the accuracy of the results and the mean obtained is more general and covers different values.
2. Inorganic or artificial soil has a different liquid limit, plastic limit, and the water content associated with it thus resulting in a different result. Unlike those soils, clay contains organic matter and clay minerals. If the soil contains different minerals then the composition will be different from clay and thus the result as well.

Due to this factors the rest of the studies were unable to obtain similar result as Wroth and Wood (1978) result. However, in this study vane shear test will be used to measure the un-drained shear strength. The sample number is also small in comparison to the original study (10 samples). The soil type depends on the site from which it is obtained and it is a mixture of different grain size and minerals.

The bottom line is this study used smaller sample size, and a different soil composition. The results will show the extinct and accuracy of the factors identified in this analysis.

All the researchers found there is a strong correlation between shear strength and water content. Where the shear strength decreases as the water content increases as shown in Fig.2. Because the cohesion and density of the soil decreases as the water content increases.

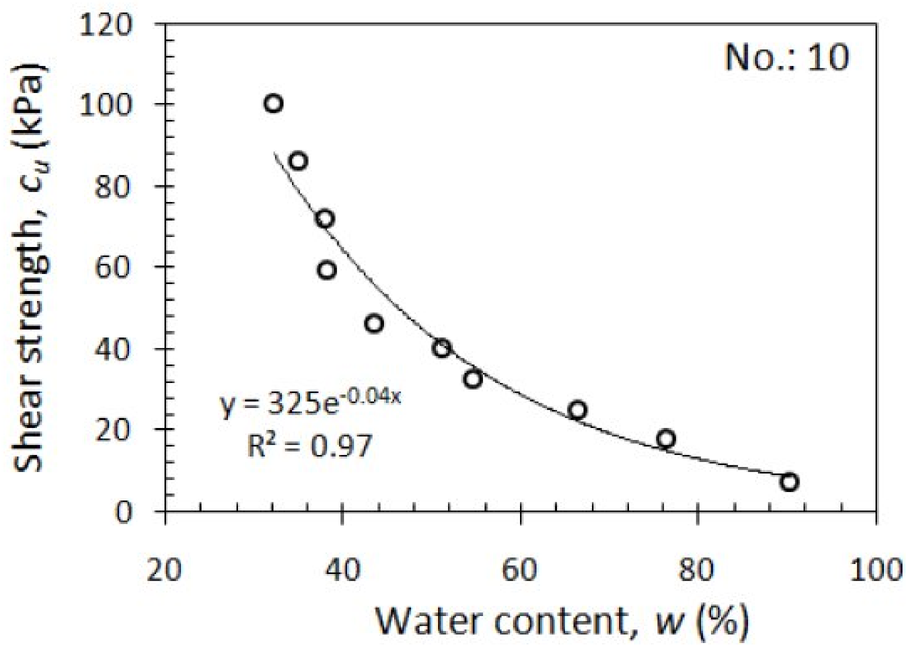

Figure 2: Shear strength vs. water content (Kayabali, 2011)

2.2. Correlation of Electrical Resistivity with Various Geotechnical Parameters

2.2.1. Comparison Between Different Studies

Table 2: Comparison between different studies

Study	Soil Type	Test Used	Sample size	Results
Cosenza et. al. (2006)	Silt, clay, coarse sand, and limestone	ρ = ERT *v* = DCPT	Unspecified area size 20 sample	good correlation between ER and cone penetration Satisfactory correlation between ER and *w/c*
Ozcep et. al. (2009)	Mixture soil (Silt, clay, coarse sand)	VES (vertical electrical sounding)	Unspecified area size	Good correlation between ρ and *w/c*
Chik et. al. (2012)	Mix of Sand, silt, clay, and gravel	High resistance meter	21 samples	increase of ρ with increase percentage of sand and gravel
Irfan and Baharom (2012)	Mix of Sand, silt, clay, and gravel	VES	12 samples	Non-liner, reverse, and good correlation between ρ and *w/c*

Study	Soil Type	Test Used	Sample size	Results
Irfan and Baharom (2013)	43% - silty sand 36% - coarse grained	VES	79 samples	Non-liner, reverse, and good correlation between ρ and *w/c* Reverse, and good correlation between ρ and PI for silty-sandy and sandy soils ρ will increase with D_{10} for all type of soils and silty-sandy soil ρ will increase while D_{10} decreases for sandy soil
Sudha et al (2009)	Mix of gravel, sand silt, and clay. Gravel dominating	ERT	17 locations	reverse, and good correlation between ρ and w/c The smaller the grain size, lesser the electrical resistivity A linear relationship between ρ and cone penetration (DCPT) and SPT
Hazreek et al (2013)	Mixture of gravel, sand, silt, clay	ERT	3 locations	reverse, and good correlation between ρ and w/c increase of ρ with increase percentage of sand and gravel

2.2.2. Electrical resistivity of soils and rocks

Electrical conductivity (or resistivity) is a bulk property of material that describe how well a material allows electric currents to flow through it. Resistivity is the resistance per unit volume. While conductivity is the inverse of resistivity, represented by $\sigma = 1/\rho$.

Conductivity of rocks varies due to rock type, porosity, connectivity of pores, nature of the fluid, and metallic content of the solid matrix. The range of electrical conductivity of different types of rocks is indicated below

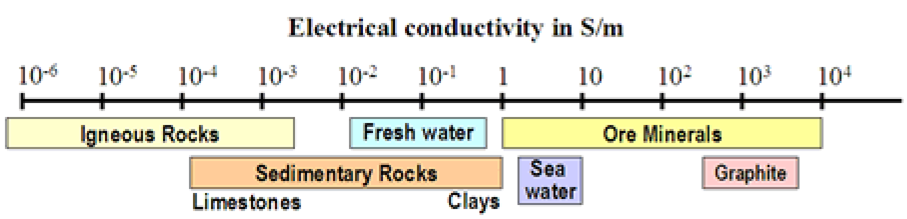

Figure 3: Electrical conductivity in different minerals and rocks

Metallic ore minerals are very rare compared to crustal minerals. They are electronic semiconductors which resistivity is lower than metals and vary because of impurities. These metallic ore are Pyrrhotite (FeS), Graphite (C), Pyrite (FeS_2) Galena (PbS) and magnetite (Fe_3O_4) Bornite ($CuFeS_4$), chalcocite (Cu2S), covellite (CuS), ilmenite ($FeTiO_3$), molybdenite (MoS_2), and the manganese minerals holandite and pyrolusite.

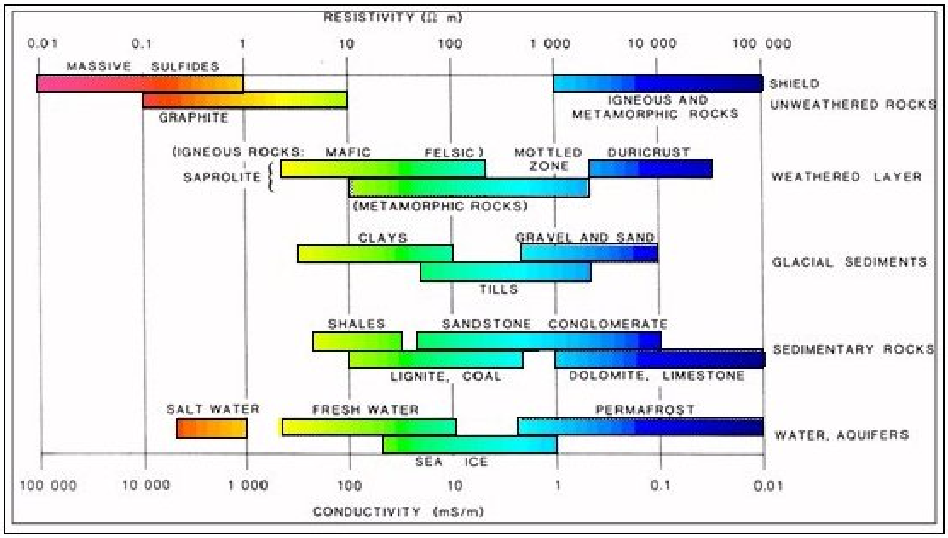

Figure 4: electrical properties of rocks

Soils and rocks are mostly composed of silicate minerals, which are fundamentally insulators. The exceptions include magnetite, specular hematite, carbon, graphite, pyrite, and pyrrhotite. Therefore, conduction is largely electrolytic, that is due to the movement of ions in a fluid or water, and conductivity depends on:

1. Porosity,
2. Hydraulic permeability, which describes how pores are interconnected,
3. Moisture content,
4. Concentration of dissolved electrolytes,
5. Temperature and phase of pore fluid,
6. Amount and composition of colloids (clay content).

Porosity or void fraction is a measure of the void spaces in a material, and is a fraction of the volume of voids over the total volume. Porosity exits in the form of joints, fractures, vugs (dissolved pockets in limestones and dolomites), and intergranular voids in sedimentary rocks. The most influencing factors of porosity is pores space and geometry. Porosity ranges from 20% to 70% for most unconsolidated materials (i.e. for soils). However, it is not common to have a large range of porosities in one site. As noted above, porosity is the primary property related to resistivity, hence the difficulty in distinguishing between sand and gravel with the same porosity.

Table 3: porosity ranges for soils and rocks

TABLE 5. Representative porosity ranges for sedimentary materials (after D. K. Todd [12])

Material	Porosity, %
Soils	50–60
Clay	45–55
Silt	40–50
Medium to coarse mixed sand	35–40
Uniform sand	30–40
Fine to medium mixed sand	30–35
Gravel	30–40
Gravel and sand	20–35
Sandstone	10–20
Shale	1–10
Limestone	1–10

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TABLE 6. Porosity of soils and rocks (after C. A. Helland [14])

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Rock or Formation	Porosity	Ratio $\frac{\rho_s}{\rho_1}$
Igneous and metamorphic rocks	½– 2	100
Dense limestones and sandstones	3– 4	50 –100
Clays and sands in general	8–15	20 – 40
Porous clays, sands, sandstone, cellular limestones, and dolomites	15–40	3 – 20
Marl, loess, clay, and sandy soil	40–75	1.5– 4
Peat, diatomaceous earth	80–90	1.0– 1.5

The "Ratio" column is bulk resistivity divided by electrolyte resistivity (see Archie's law below).

If the pores are not interconnected, that leads to low hydraulic permeability, preventing the fluid of flowing throughout the soil, resulting in a low resistivity. Therefore, hydraulic permeability and porosity together play an important role in soil resistivity.

Archie's rule relates porosity to water conductivity as follow $n^m = \sigma_x/\sigma_1$ *(Eq. 6)*

Where σ_x is bulk conductivity, σ_1 is connate water conductivity, n is porosity, and m is a constant.

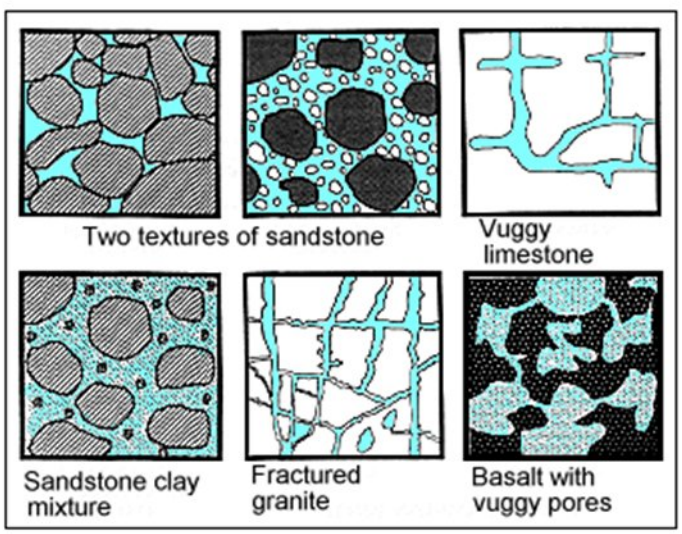

Figure 5: Porosity and permeability of different soils and rocks

The figure below shows that electrical resistivity decreases as the permeability and porosity increases which is consistent with Archie's law

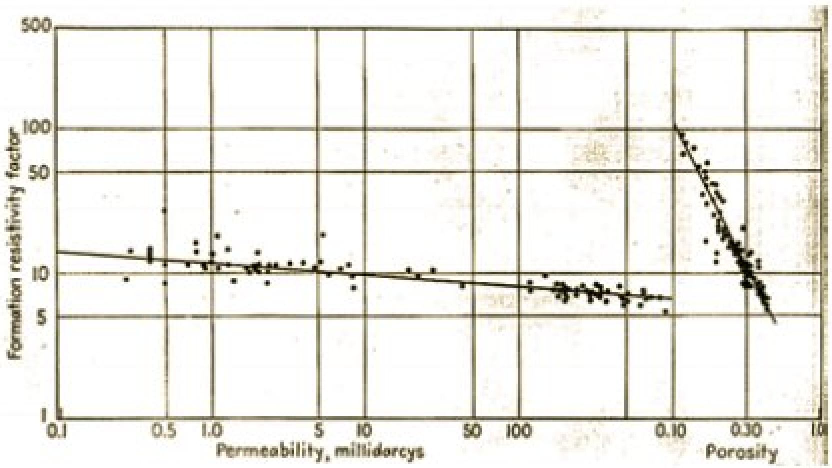

Figure 6: Relationship between permeability and electrical resistivity (Archie, 1942)

Conductivity of fluids depends on quantity and mobility (velocity) of charge carriers.

Flow of current in a cylinder with length L and A cross-section result in electrical resistivity express as follow $\rho = E/ nqv$ *(Eq. 7)*

This clearly show that electrical resistivity decreases as mobility increases.
Mobility depends on viscosity of fluid (hence temperature) and diameter of charge carriers. Fluid conductivity depends on temperature because the mobility of the ions in solution increases with temperature. Reducing temperature reduces electrolytic activity, and thus conductivity. The figure below shows this effect in terms of resistivity.

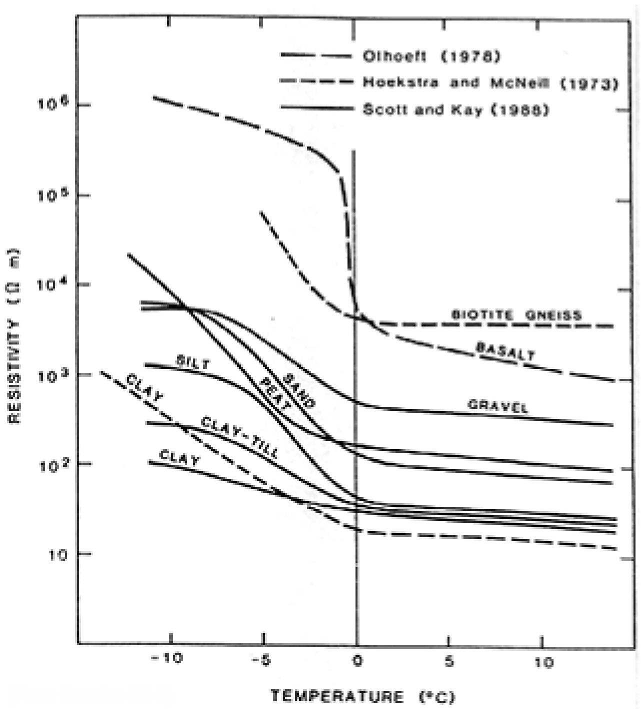

Figure 7: relationship between temperature change and electrical resistivity

Electrical resistivity is influenced by salinity of the soil. Salinity increase electrical conductivity because when water is dissolved in water it allows Na and Cl ions to travel freely in the fluid resulting in an increase of the ions concentration.

The law that relate moisture content to conductivity is

$$S_w = \frac{\text{volume of water in pores}}{\text{total volume of pores}} = \left(\frac{a\rho_w}{\phi^m \rho_t}\right)^{(1/n)}$$

(Eq. 8)

S_w, in clean (no clay) formations, where □ is porosity, ρ_w is resistivity of water, ρ_t is total resistivity, and a and m are both empirically calculated constants. Using this, conductivity seems to be very small for low moisture contents. However, the addition of water to material is critical in affecting conductivity, and slightly wet materials are much more conductive than dry materials.

Colloidal conductivity (conductivity due to clay) is a result of Cation Exchange Capacity (CEC) of clay in the double diffuse layer that forms at the interface of the clay mineral and water. Where the charges (cations) can be adsorbed (attached to the surface) onto the slightly negatively charged surface, and these can subsequently be exchanged or dissolved. This allows ions to move with higher mobility than in the liquid phase. As shown in the figure below

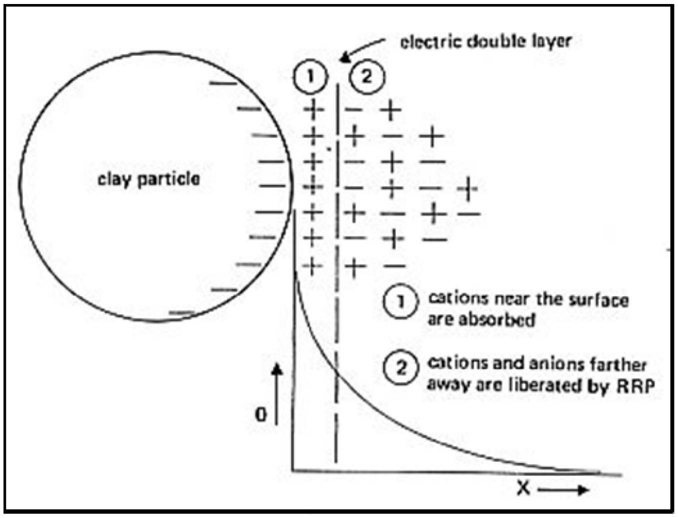

Figure 8: Clay double diffuse layer

Since clay has a huge surface area to volume ratio, it has a much higher exchange capacity. This is especially the case with the clays vermiculite and montmorillonite. Therefore, clays can dramatically increase the conductivity of fresh waters. Saline waters may not have much more capacity to absorb extra electrolytes.

2.2.2. Analysis of the electrical resistivity correlation studies

The results from different studies were consistent and identical despite the variation in the soil type; test used, and sample size or number of locations or sites. This is because the electrical resistivity is affected by the moisture content of the soil, salinity, porosity and permeability, and clay percentage. Since the effect of these factors is constant among all type of samples, the sample number is of no significant influence.

There is a good correlation between electrical resistivity and water content. The reverse relationship between electrical resistivity and w/c exist because higher moisture content facilitates conduction of electrical current through movement of ions in pore water, and thus reduce the soil resistivity, as shown in the Fig.3 below.

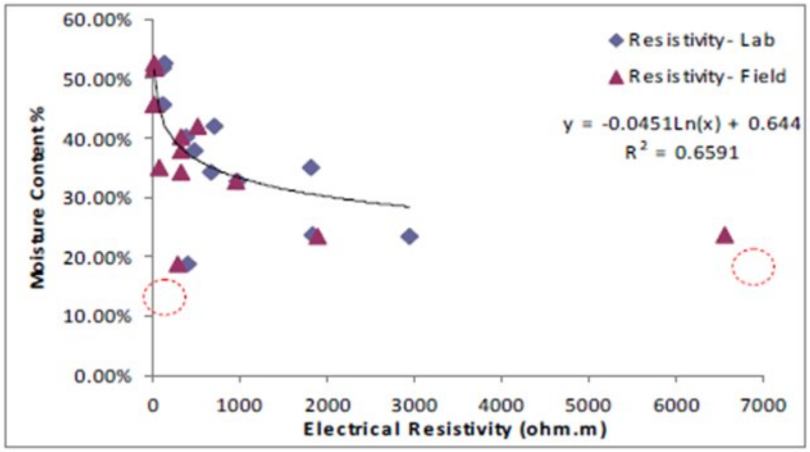

Figure 9: Electrical resistivity vs. moisture content (Irfan & Baharom, 2012)

There is an acceptable correlation between electrical resistivity and plasticity index (PI) for silty-sandy and sandy soil results from high PI which indicate a high liquid limit and high water content results in low electrical resistivity.

The effective size (D10) is the maximum diameter of soil particles corresponding to 10% passing on a grain-size distribution curve. Some studies have related effective size to electrical resistivity for different type of soils (Baharom & Irfan, 2012). Resistivity will increase with D10 for all type of soils and silty-sandy soil because the fine particles tends to reduce the permeability and affects the transmission of fluid thus resulted in increase of resistivity in silty-sand soil. Resistivity will increase while D10 decreases for sandy soil because sandy soil have larger grain size that results in high permeability that facilitates the transmission of ion in pore fluid, which in turn reduce the electrical resistivity.

The electrical resistivity of the soil will decrease as the percentage of clay increases, due to the CEC capacity of the clay. Hence, a low percentage of clay result in high resistivity and vice versa. Thus, it stand to reason to say that the higher percentage of either clay or sand indicate the resistivity of the soil. In this study, sand percentage was taken as the defining factor because it has a higher percentage than clay. The figure below show the influence of soil grading on electrical resistivity (Hazreek et al, 2013)

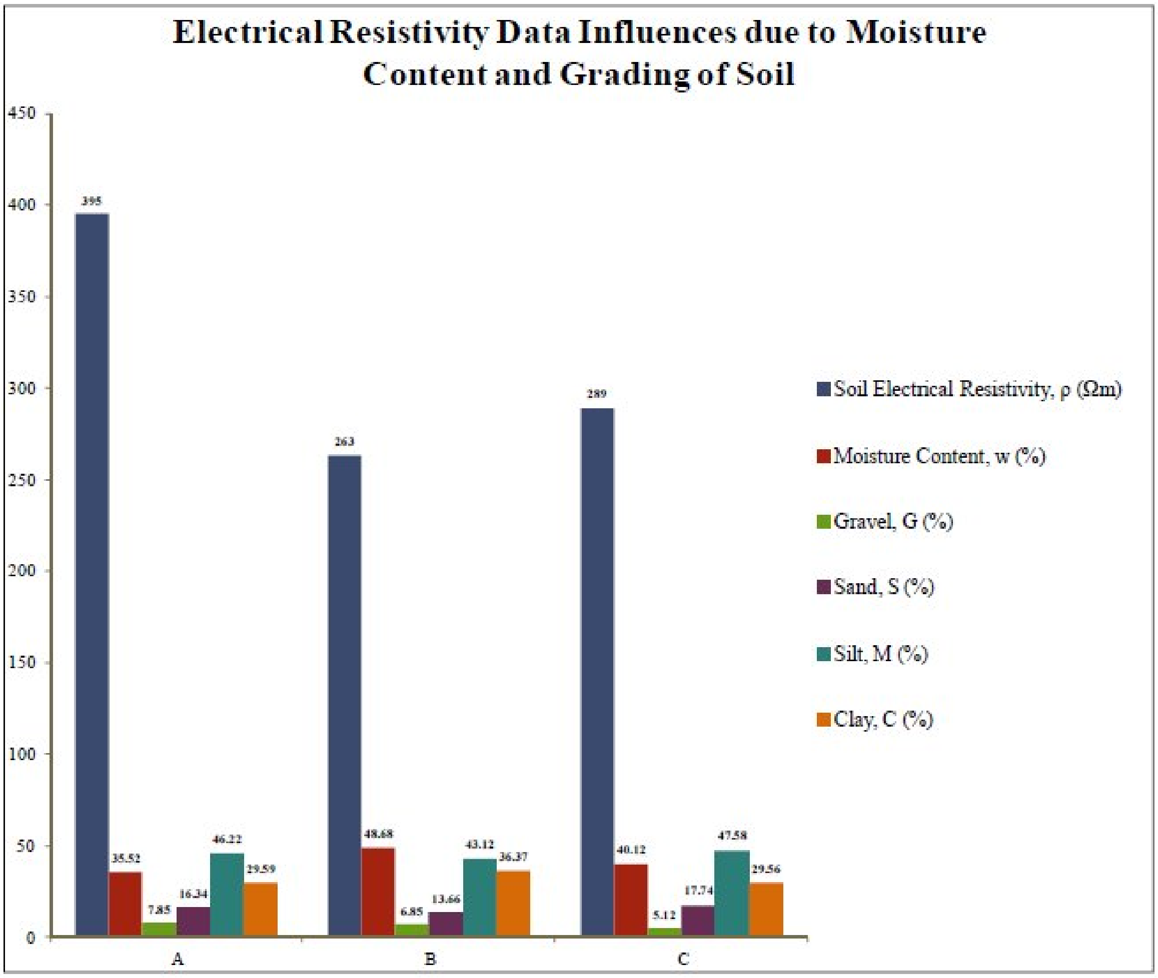

Figure 10: Electrical resistivity data sue to moisture content and soil grading

2.3.Application

The correlation between shear strength and other soil properties can provide conservative values against which the results obtained from the common strength tests can be assessed with an inbuilt margin of safety (Wood, 1990; Sharma and Bora, 2003).

This approach is useful when important design decisions have to be made based on or poor quality soil. In such situations, it is valuable to have a lower acceptable value of shear strength by assessing its remoulded strength. The correlation have a specific and practical application to offshore site investigation, where good quality samples and test results are very costly and difficult to obtain. The samples are likely to be in in a disturbed state. Other than providing a benchmark for comparing test results, it also suggest whether a soil have some strange properties that should be further investigated.

In the case of natural deposits of soft normally consolidated clay, the *in situ* strength is underestimated by a substantial margin due to its high sensitivity. On the other hand, the remoulded strength might is overestimate the *in situ* strength by a substantial margin due to its low sensitivity of over consolidated clays.

3. METHODODLOGY

3.1. Research methodology

3.1.1. Sample acquisition and preparation

The soil samples were obtained from different places, randomly. To ensure varieties of soils are included as much as possible. The soil samples were obtained from the surface, using a shovel or scrapped of the surface if it is a loose soil.

The samples preparation included drying them in the oven for 24 hours if they were wet, followed by crushing the samples into small little pieces using a hammer. Finally to be able to find its plastic and liquid limit; they were sieved in the 425μm sieve.

3.1.2. Liquid Limit determination

Cone penetration test was used to measure the samples liquid limit. Where 300g of the sample was taken and distilled water was added gradually and then mixed using spatulas. Afterwards the penetration was recorded at each addition of water and a small part of the sample was placed in a tray, weighted, and put in the oven for 24 hours. This was done repeatedly until the penetration reached 20 or above.

After 24-hours, the samples were weighted and the plastic limit was calculated as follow:

LL= (mass of moisture / mass of soil) x 100 *(Eq. 9)*

The liquid limit was taken as the point where the liquid limit line intercept the penetration line at 20. For most cases, it was a bit above the calculated average of the liquid limits.

3.1.3. Plastic limit determination

The plastic limit was determined using the thread rolling method. Where a small amount of distilled water was added to 10g of the sample, rolled into a ball then divided into four parts and 3-4 threads of 3-5mm was made from each partition. Those threads were placed in a tray, weighted, and put in an oven for 24 hours.

The next day the weight of the sample was recorded and the plastic limit was calculated as follow: *PL= (mass of moisture / mass of soil) x 100* *(Eq. 10)*

The average of the four liquid limit obtained from the four parts represent the sample plastic limit

3.1.4. Sample mixing

After the plastic and liquid limit for each sample was measured. It was time to prepare the sample for electrical resistivity and shear strength test. To do so, the samples must be prepared at their respective liquid and plastic limit.

1.7kg of the sample was placed in a mixer, and distilled water was added in respect of their plastic and liquid limit and then mixed for 10 minutes. Then the sample was covered with plastic bag and left to soak for 24 hours in the room temperature of about 27ºC.

3.1.5. Electrical Resistivity determination

The electrical resistivity was calculated indirectly from the resistance measurement. The resistance was measured in the lab using a DC power source and a multimeter, for each sample at plastic and liquid limit.

At plastic limit, the sample was compacted using a compactor. However, to prevent short circuit from the steel mould a plastic sheet was placed between the soil and the mould before compaction.

At liquid limit the soil was compacted in a small plastic cylinder, since the high water content prevent it from being compacted properly using a compaction machine.

The resistivity law was used to calculate the resistivity as follow:

$$\rho = RA/L \qquad \text{(Eq. 11)}$$

Where, A= the cross sectional area of the sample, i.e. the mould area = πr^2

L = length of the mould

ρ=resistivity

$$R = resistance = V/I \qquad \text{(Eq. 12)}$$

Where; v = the voltage, and I= current in (A)

The resistivity was taken as the average of the resistivity obtained at 30A, 60A, and 90A respectively.

Table 4: Specification and functions of mulitmeter used

	Specifications	Functions		
Insulation Resistance Tester- Digital	Test Voltage	1000 V and 600 V		
	Measuring ohms Ranges	10 Ω to 1 GΩ with up to 10 µΩ resolution		
	Measuring current ranges	100 µA to 10 A current range, with up to 100 pA resolution		
	Measurement technique	2 x 4 ohms 4-wire		
Insulation Resistance Tester-Analog	Test Voltage	DC 1000 V	DC 500 V	DC 250V
	Measuring ohms ranges	0~400 MΩ	0~200 MΩ	0~100 MΩ
	Mid-Scale Value	4 MΩ	2 MΩ	1 MΩ

3.1.6. Shear strength determination

Vane shear test was used to measure the shear strength. Where a small amount of sample was compacted in a small steel cylinder and a torque was applied on the soil by the rotating vane at the rate of 6º/min - 12ºmin, until the soil has sheared.

The shear strength of the soil was calculated as follow

$$T_v = (M / K)\ kN/m^2 \qquad (Eq.\ 13)$$

M = torque applied to shear= maximum angular rotation X calibration factor

$$K = \Pi D^2\ [(H/2) + (D/6)] \qquad (Eq.\ 14)$$

Where; D= the vane width = 12.76 mm

H = length of the vane = DX4 = 51.04mm

Spring 3 and 4 were used at plastic and liquid limit respectively. The same vane shear apparatus, thus the diameter and height is the same for all the samples.

3.1.7. Particle size distribution determination

Since the soil samples obtained are very fine and the sieve test was impractical to measure its size distribution, another method was adopted. Hydrometer test was used according to BS 1377 part 2 1990, 9.6 standard.

50 g of the sample was placed in a conical flask and 100ml of sodium hexametaphosphate was added and mixed in the shaker for 24 hours. The next day the sample was sieved through 63µm sieve. Two procedures were followed with the retained and passing mass, to be able to generate a size distribution graph that represent the size variation throughout the soil sample.

The mass passing 63µm was placed in a 1000ml cylinder and placed in the water bath and readings were taken at 30s, 1min,4min, 8min, 15min, 30min, 1 hours, 2 hours, 4 hours, and 24 hours using a hydrometer. On the other hand, the mass retained on 63µm was washed off on a tray using distilled water and placed in the oven for 24 hours. The next day the dry sample was sieved through 1.18mm, 600μm, 425μm, 300μm, 212μm, 150μm, and 63μm respectively.

To calculate the mass percentage in the 1000ml cylinder, the following equations were used;

$R_h = R_h' + C_m$ (Eq. 15)

Where; C_m = the meniscus correction = 0.5mm

R_h= hydrometer reading

D = Particle diameter = $0.005531\sqrt{(\eta H)/(\rho s - 1)\, t}$ (Eq. 16)

Where; η = water viscosity = 0.857 mPa.s at 27ºC, and ρs = 2.65 Mg/m^3

H_R= effective depth = $H + 0.5 [(h -(V_h L/90)] = 189.67-3.8321R_h$ (Eq. 17)

T = time elapsed

The modified hydrometer reading, $R_d = R_h' - R_0$ (Eq. 18)

Where; R_0 = 0.5mm

$D= [100\rho s/m (\rho s - 1) X R_d$ (Eq. 19)

D= the percentage by mass passing, K smaller than the equivalent particle size

m = mass of dry soil = 50 g

To calculate the mass percentage in the dried sample, after sieving it, the percentage of mass retained, and the cumulative percentage passing each sieve was calculated and represented in the graph. The resultant graph of percentage passing vs particle size mm represent the size distribution for the entire 50 g sample. Starting from clay, to silt, to sandy size. The percentage of sand, silt, and clay was taken from the distribution of the particle sizes in that graph.

3.2. Gantt Chart and Key Project Milestone

The Gantt chart shows the schedule activities, the period of each activity, and critical tasks such as presentations and report submissions throughout the two semesters.

3.2.1. FYP 1 Gant Chart:

The Gantt chart for FYP I is planned and shown in figure below

Table 5: FYP1 Gantt chart

Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14
FYP briefing														
Project outline														
Extended proposal submission														
Sample collection														
Proposal defense														
Interim Report submission														

FYP 1 Key Mile Stones:

1. Title selection — Week 2
2. Submission of extended proposal — Week 8
3. Proposal defense — Week 10
4. Submission of interim report — Week 14

3.2.2. FYP 2 Gant Chart:

Table 6: FYP2 Gantt chart

Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Lab tests														
Progress report submission														
Result Analysis														
Pre-SEDEX														
Submission of report														
Viva														
Submission of dissertation (hard bound)														

FYP 2 Key Mile Stones:

1. Result analysis — Week 10
2. Pre-SEDEX — Week 10
3. Submission of technical report — Week 12
4. Viva — Week 13
5. Submission of Dissertation report — Week 14

4. RESULTS AND DISCUSSION

The results obtained from the ER and shear strength tests for the 10 samples are shown below according to the samples respective LL and PL

Table 7: Results

Sample Number	Plastic Limit (%)	Plastic limit (%)		Liquid Limit (%)	Liquid limit (%)		Hydrometer Sand %
		C_u Kpa	ρ Ω.m		C_u Kpa	ρ Ω.m	
1	40	62	134	60	0.17	50	69.69
2	30	90	180	70	0.17	15	78.98
3	19	270	180	30	1.54	25	99.67
4	26	168	349	48	1.07	291	92.66
5	25	207	638	47	0.17	322	94.45
6	19	161	616	30	8.58	467	91.39
7	22	8.88	635	38	0.17	365	99.94
8	28	361	437	43	4.5	203	99.86
9	28	8.92	579	49	0.17	76	99.81
10	7	16.81	1508	27	0.26	204	99.4

The relationship between the different parameters are represented by a graph where its trends and features are discussed and explained as follow

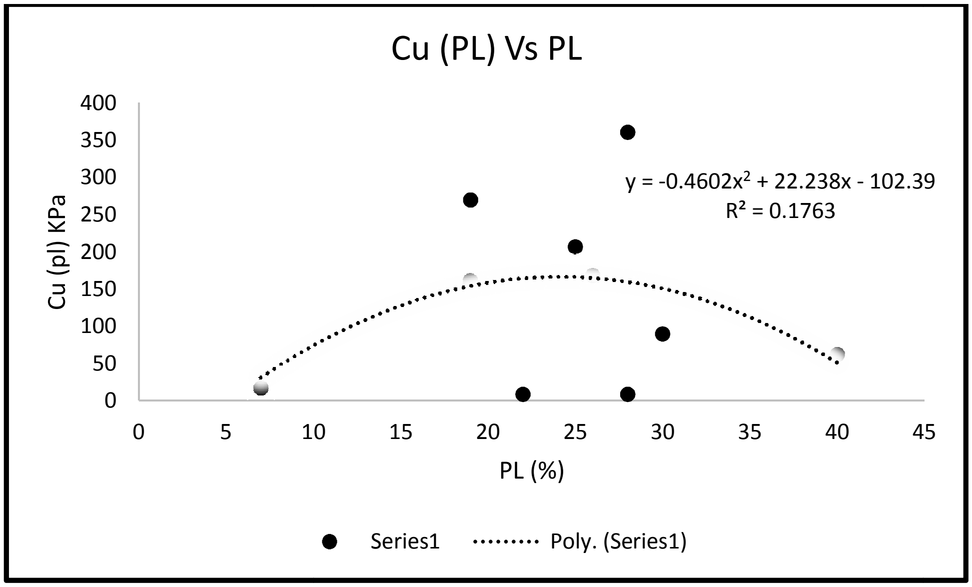

Figure 11: Cu (PL) VS. PL

The graph shows that the shear strength increases as water content increases until it reaches 25% water content. Afterwards, the shear strength decreases as water content increases.

The shear strength increases in the beginning until it reaches 25% because when water is added to a dry sample it increases its cohesion, density, and strengthen the bond between its particles; as a result, the shear strength increases as well. When the water content reaches 25%, the shear strength reaches its maximum value of approximately 160 kPa. Beyond this ultimate water content, the shear strength decreases as water content increases. Since after 25% the water will fill all the voids between the particles and separate the particles from each other, thus decreasing their cohesion and density, the shear strength will decrease as well.

Though the correlation coefficient is quite small which suggest a poor correlation. It helps us understand the behaviour of shear strength at plastic limit with the plastic limit.

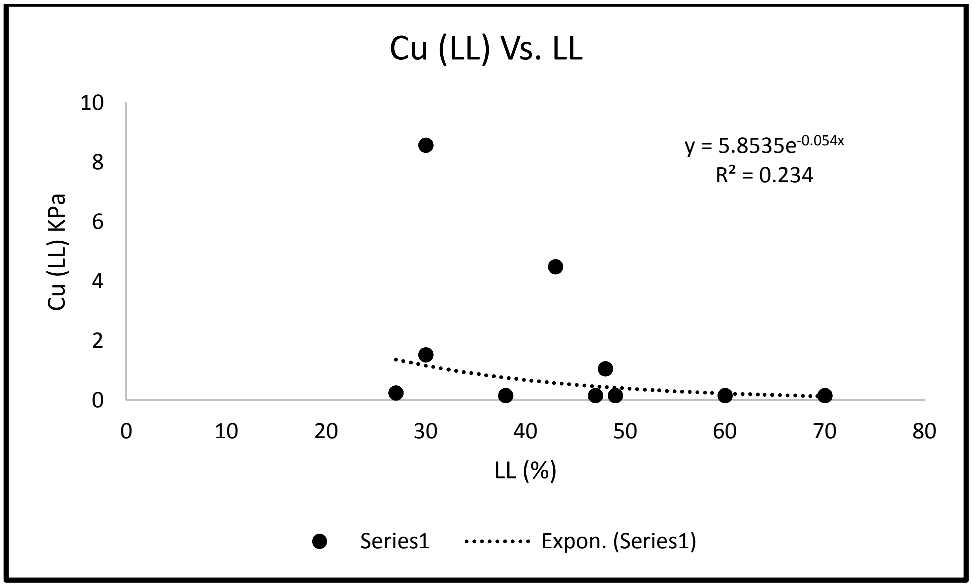

Figure 12: Cu(LL) VS LL

The graph shows that the shear strength decreases after 25% water content as the water content increases. As was explained before when the sample is saturated with water, its cohesion decreases and as a result its strength.

This result is consistent with the result obtained from the graph of C_u at plastic limit and PL. It is also consistent with the results obtained from other researchers. The study of shear strength conducted by Kayabli (2011) on 120 samples of remolded clay using vane shear test, showed a very strong correlation ($R^2 = 0.97$) between shear strength and water content. Skemptoon and Northey (1953) obtained the same good correlation.

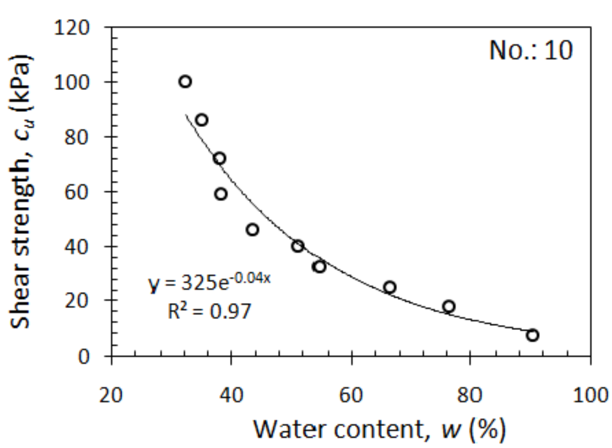

Figure 13: Cu VS. Water content (Kayabli, 2011)

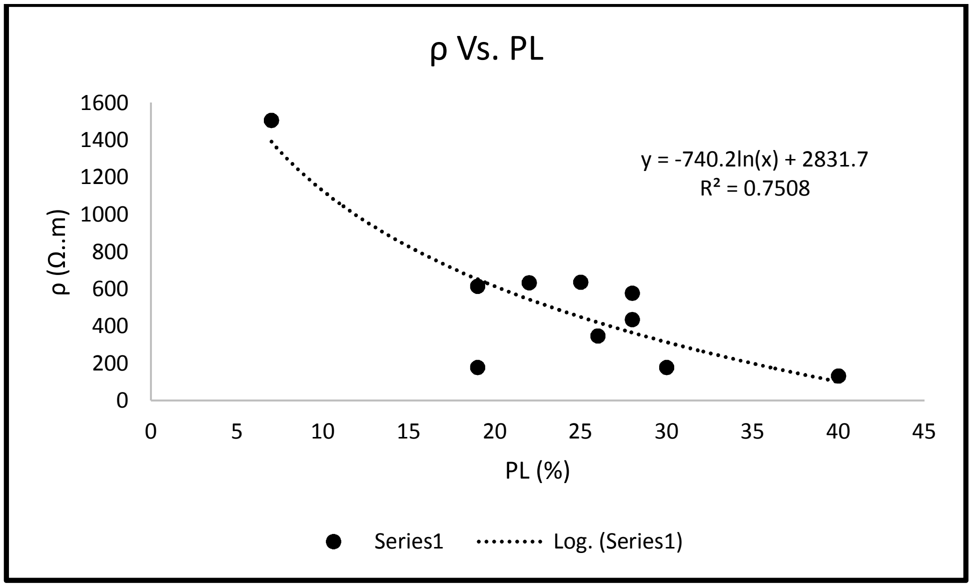

Figure 14: Resistivity VS. PL

The graph shows that electrical resistivity decreases when the water content increases. This is because the water trapped in the soil pores and between the particles facilitate the transfer of current through the movement of ions. Thus, when the conductivity of the soil is increased, its electrical resistivity decrease.

There is a strong correlation between electrical resistivity and PL. The same result was obtained from other studies, such as Cosenza et. al. (2006), Ozcep et. al. (2009), Irfan and Baharom (2012), Irfan and Baharom (2013), Sudha et al (2009), and Hazreek and Chitral (2013).

It should be noted that the studies mentioned above correlated the shear strength to the water content of the samples in general, not a specific Atterberg limit. As shown below

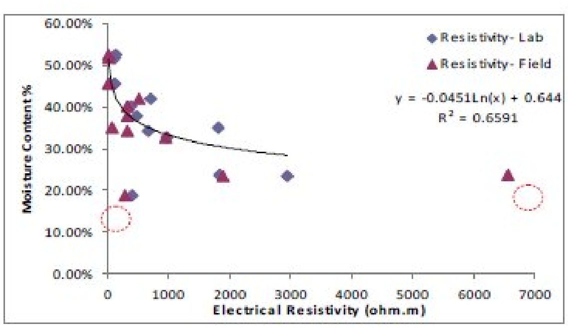

Figure 15: Resistivity VS. Moisture content (Irfan and Baharom , 2013)

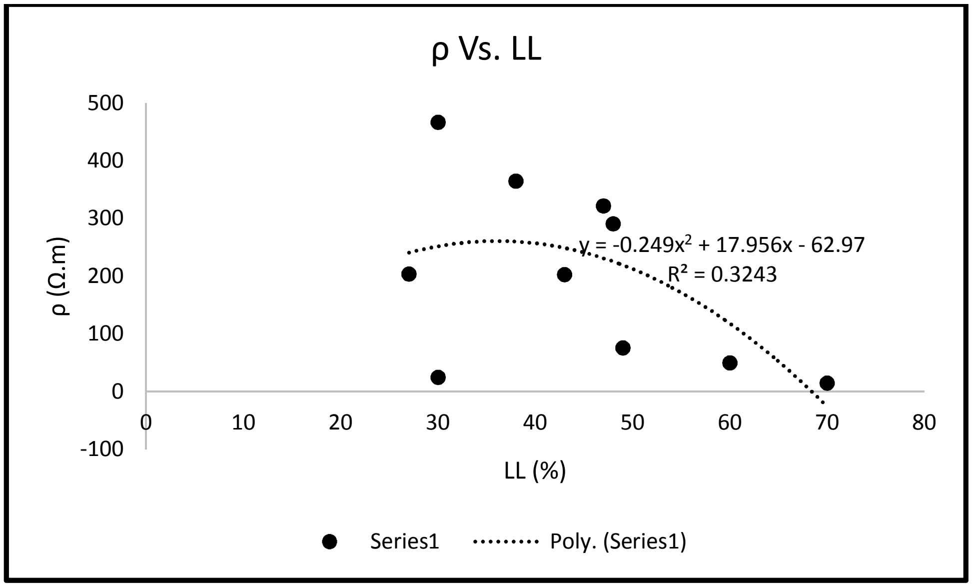

Figure 16: Resistivity VS. LL

The graph shows that the electrical resistivity at LL increases with water content until it reaches approximately 35 % then it decreases as water content increases.

Electrical resistivity incensement with water content can be attributed to many reasons; such as:

1. Salinity change: If the salinity of the samples decreased from high salinity to low salinity gradually. The electrical resistivity can increase as well. Salts provide additional ions to the water that result in a low resistivity. Then the salinity increased again gradually, resulting in a low resistivity.
2. Hydraulic permeability variation: If the permeability of the samples increased from low to high, then decreased gradually, it can result in decrease of electrical resistivity.
3. Porosity variation: a variation of porosity space and geometry along the soils samples from low to high and low again can result in this polynomial relationship.

These factors did not affect the electrical resistivity at PL because the flow of current was already limited by the min amount of water present in the pores. Thus, these factors had a min impact on the resistivity at plastic limit. The point where the electrical resistivity start decreasing represent the point of the gradual consistent change in porosity or salinity or hydraulic permeability. The temperature wasn't included as a factor because all the tests were done in the laboratory at a consistent temperature of 27ºC.

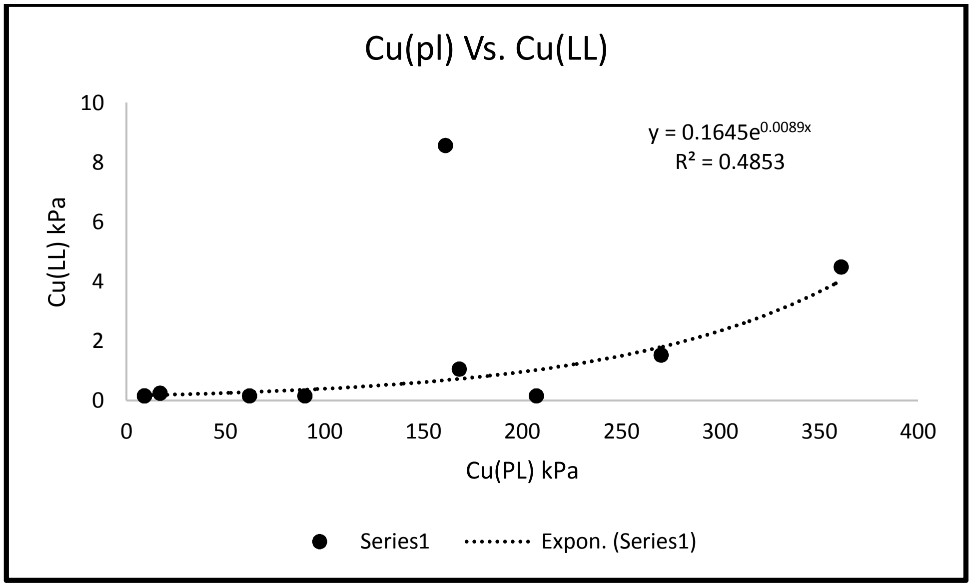

Figure 17: Cu (PL) VS. Cu (LL)

The graph shows a proportional relationship, where the shear strength at plastic limit increases as the shear strength at liquid limit increases. The shear strength in general whether at plastic or liquid limit decreases as water content increases because water separate the particles and decreases the cohesion and density of the soil. Therefore, it is expected that the shear strength at the two limits are proportional to each other.

There is a moderately strong correlation between the two parameters. Which suggest a relationship between them.

The average of C_u (PL) = 135.361

The average of C_u (LL) = 1.68

Thus, the correlation factor, R = 135.361/ 1.68 = 81

It should be noted that this result is different from other studies for various reasons such as the small number of samples, low accuracy of the vane shear test, and different chemical composition of the soil. The studies were conducted on remoulded clay while this study used various type of remoulded soils including one clay, kaolin, and mixture of clay, silt, and sand in different ratios.

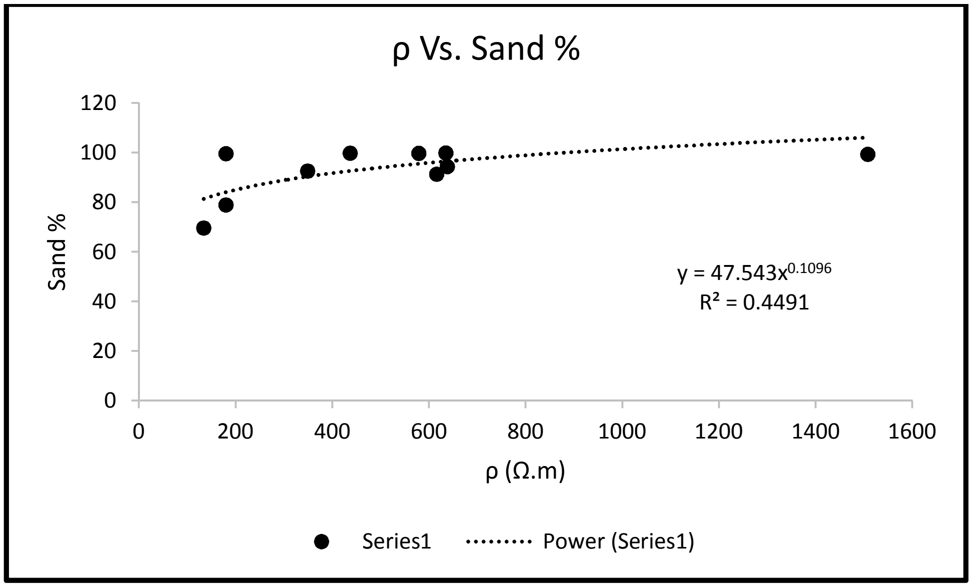

Figure 18: Resistivity VS. Sand percentage

The graph shows a direct proportional relationship whereas the sand percentage increases as the electrical resistivity increases. The same result was obtained by Chik et. al. (2012) , Sudha et al (2009), and Hazreek and Chitral (2013).

Sand is a nonconductive material; therefore, current conduction happens through electrolytic conduction. Where the current is carried by the dissolved ions in the water.

When there is a high percentage of clay in the soil, the electrical resistivity decreases. Because clay forms a double layer at the surface of interface with water. This increase the number of ions that can move current through water.

Thus, when sand percentage is higher, the current conduction is limited to the water movement. Although the silt and clay percentage affect the electrical resistivity, the influencing factor is defined by the higher percentage of sand.

In this case, other factors that can affect electrical resistivity are salinity, porosity, and permeability of the soil. Since salinity adds more ions that can conduct electricity, and the connection between the voids affect the mobility of the ions carrying the current.

5. CONCLUSION AND RECOMMENDATION

Shear strength at plastic limit vs that at liquid limit shows a proportional relationship. Because shear strength generally decrease with water content and increase with decrease of water. The variation of water content throughout the plastic limit and liquid limit is also governed by this behaviour. The shear strength at plastic limit equals 83 of that at liquid limit. It is different from results obtained from other studies due to the limited sample numbers, soil composition, and affected by the low accuracy of vane shear test.

The shear strength at plastic limit increases from 0% water content until it reaches 25% water content after which it decreases as the water content increases. The same was obtained from the graph of shear strength vs liquid limit. Showing a decrease of shear strength with addition of more water. This is because water separate the particles and decrease the soil overall density.

Electrical resistivity at plastic limit decreases as the water content increases, whereas the electrical resistivity at liquid limit increases until it reaches 35% water content then it decreases and the water content increases. This behaviour can be the result of the variation of salinity and porosity among the soil samples. This variation was not of large effect at plastic limit because the small amount of water limits the movement of current.

Electrical resistivity increases as the sand percentage increases, because high percentage of sand means low percentage of clay that result in a low contribution of additional current-carrying ions through its double diffuse layer, which ultimately lead to low resistivity. When sand percentage is high, the current is conducted by water and thus salinity and permeability is of big effect on the electrical resistivity.

Though the correlation factor for most of these parameters is low, it still show the existing relationship between these parameters. However, further investigation is needed by using a more accurate test such as triaxial test and including a larger number of soil types with different grain size.

REFRENCES

B. S., & Bora, P. K. (2003, August). Plastic Limit, Liquid Limit and Undrained Shear Strength of Soil- Reappraisal. *Journal of Geotechnical and Geoenvironmental Engineering, 129*(8), 774-777. doi:10.1061/(ASCE) 1090-0241(2003) 129:8 (774)

F. O., O. T., & M. A. (2009, June 4). Correlation between electrical resisitivity and soil-water content: Istanbul and Golcuk. *International Journal of Physical Sciences, 4*(6), 362-365.

K. K. (2011). Assesment of Shear Strength at Consisitency Limits- A Reappraisal. *Electronic Journal of Geotechnical Engineering, 16*, 1679-1693.

K. K., & Tufenkci, O. O. (2010). Shear strength of remolded soils at consistency limits. *Canadian Geotechnical Journal, 47*, 259-266. doi:10.1139/T09-095

M. I., J. R., S. K., & S. M. (2009). Soil characterization using electrical resistivity tomography and geotechnical investigations. *Journal of Applied Geophysics, 67*, 74-79. doi:10.1016/j.jappgeo.2008.09.012

O'Kelly, B. C. (2013). Atterberg limits and remolded shear strength- water content relationships. *ASTM Geotechnical Tetsing Journal, 36*, 939-947. doi:10.1520/GTJ20130012

P. C., E. M., F. R., Cui, Y. J., A. T., & Y. C. (2006). Correlations between geotechnical and electrical data: A case study at Garchy in France. *Journal of Applied Geophysics, 60*, 165-178. doi:10.1016/j.jappgeo.2006.02.003

Siddiqui , F. I., & Azhar , S. B. (2013). Simple and Multiple regression models for relationships between electrical resisitivity and various soil properties for soil characterization. *Environmental Earth Science, 70*, 259-267. doi:10.1007/s12665-012-2122-0

Siddiqui, F. I., & Azhar, S. B. (2012, March). Intergrating Geo-electrical and geotechnical data for soil characterization. *International Journal of Applied Physics and Mathematics, 2*(2), 104-106.

Wroth, C. P., & Wood, D. M. (1978, May). The correlation of index properties with some basic engineering properties of soils. *Cnadian Geotechnical Journal, 15*, 137-145.

Y. W., & Bezirci, M. H. (1986). Determination of the consistency limits of soils by the fall cone test. *Candian Geotechnical Journal, 23*, 241-246.

Z. C., & Taohidul Islam , S. M. (2012). Finding soil particle size through electrical resisitivity in soil site investigation. *Electronic Journal of Geotechnical Engineering, 7*, 1867-1876.

Z. C., Taohidul Islam , S. M., H. S., & Mustafa, M. M. (2012, October). Expert idea on liquid limit and plastic limit estimation with soil resistivity profile. *The online Journal of Scrince and Technology, 2*(4), 19-23.

Zainal Abidin, M. H., Wijeyesekera, D. C., R. S., & F. A. (2013). The influence of soil moisture content and grain size characteristics on its field electrical resistivity. *Electronic Journal of Geotechnical Engineering, 18*, 699-705.

APPENDICES

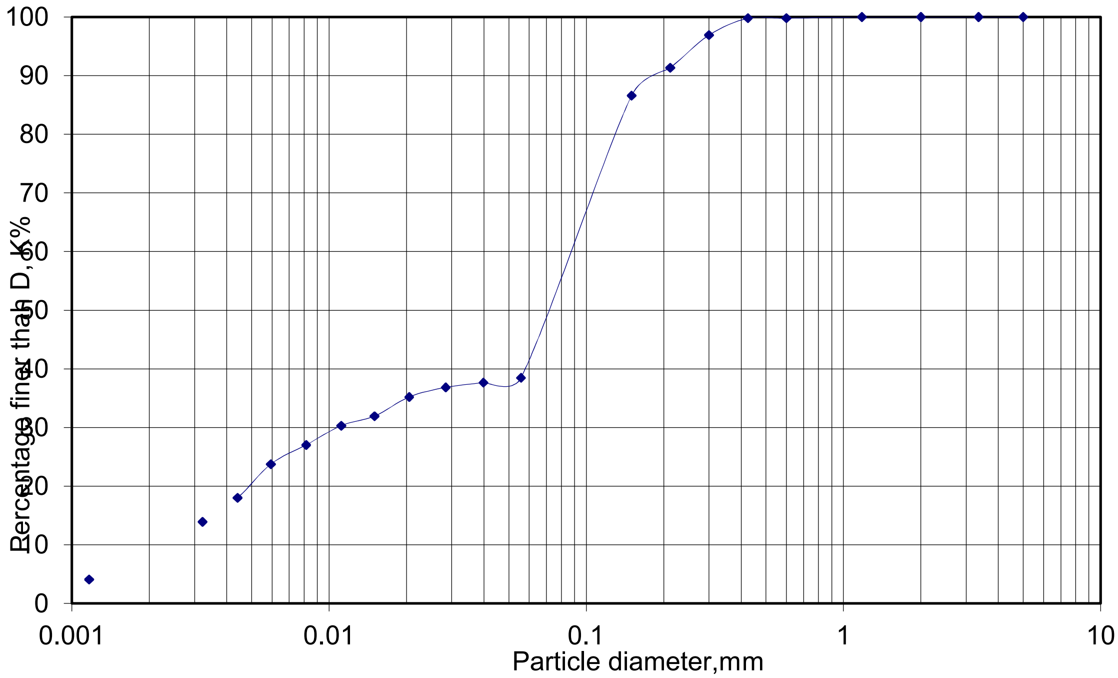

Figure 19: Sample 1 PSD

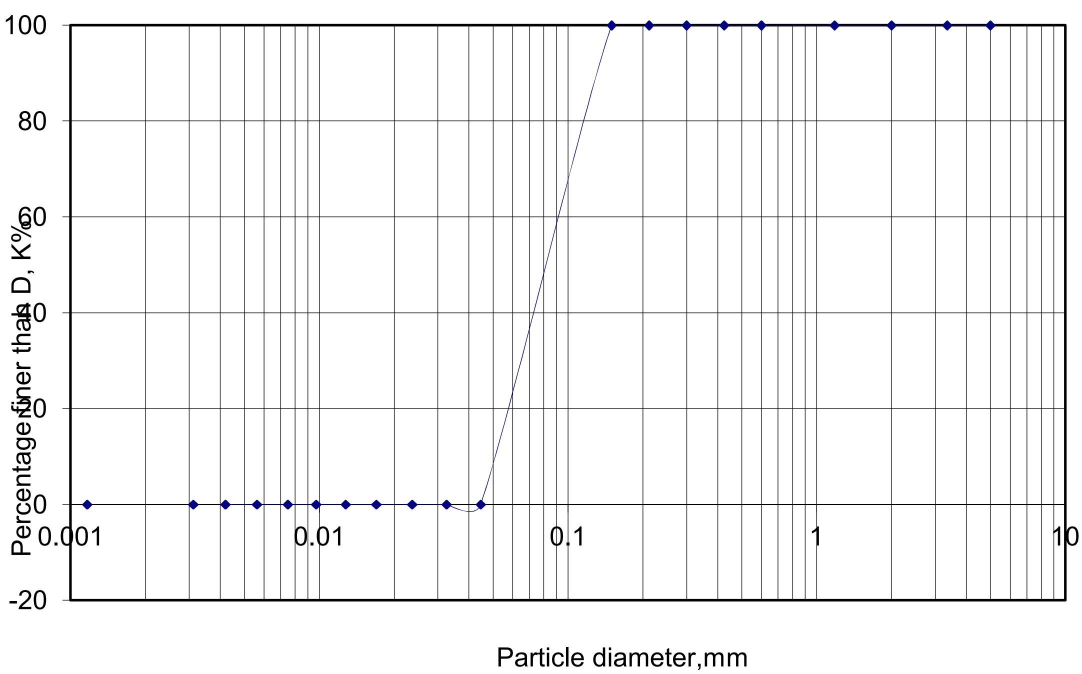

Figure 20: Sample 2 PSD

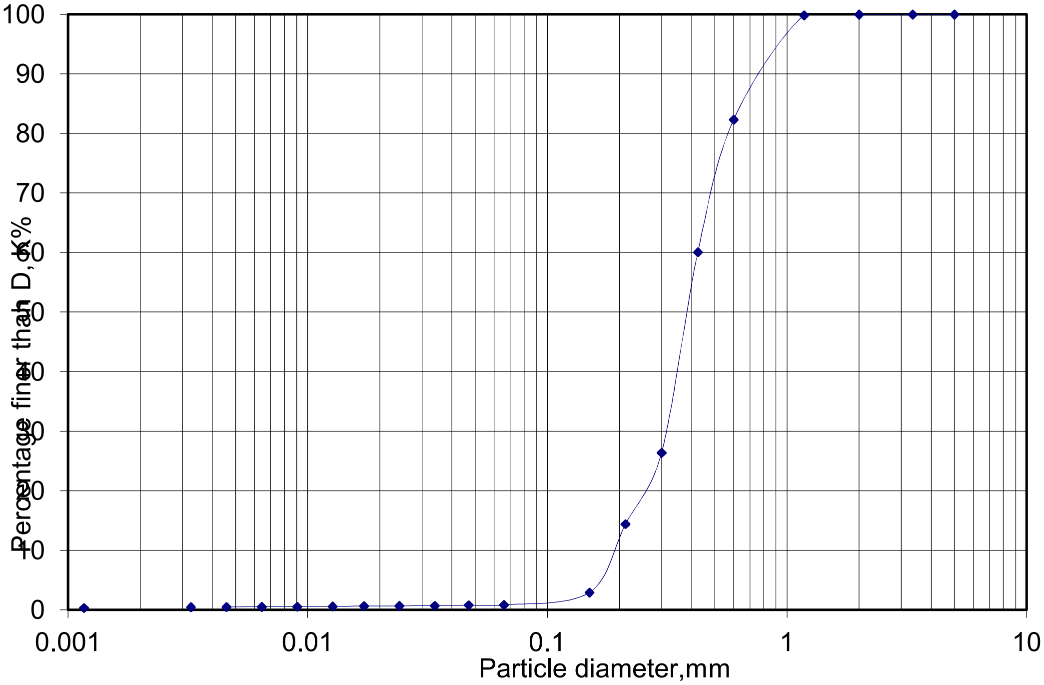

Figure 21: Sample 3 PSD

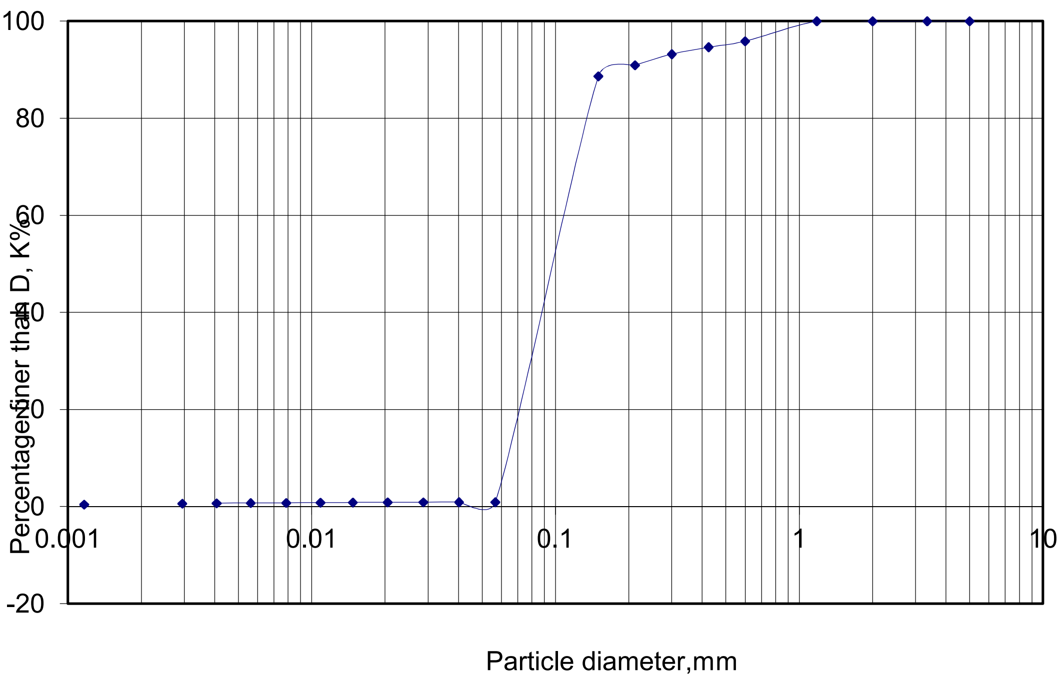

Figure 22: Sample 4 PSD

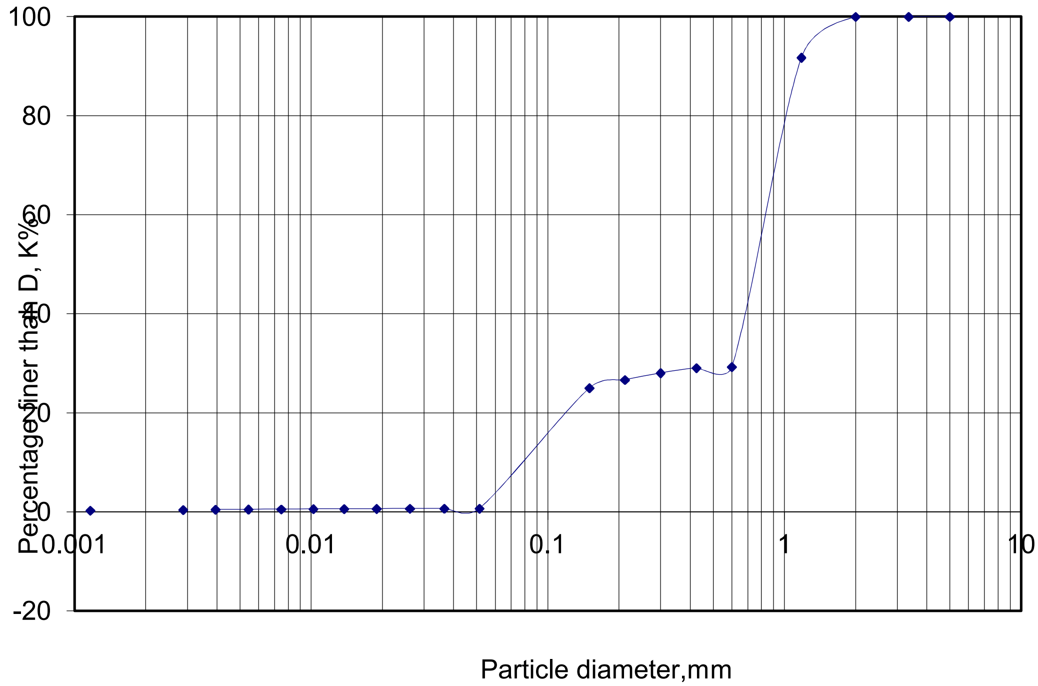

Figure 23: Sample 5 PSD

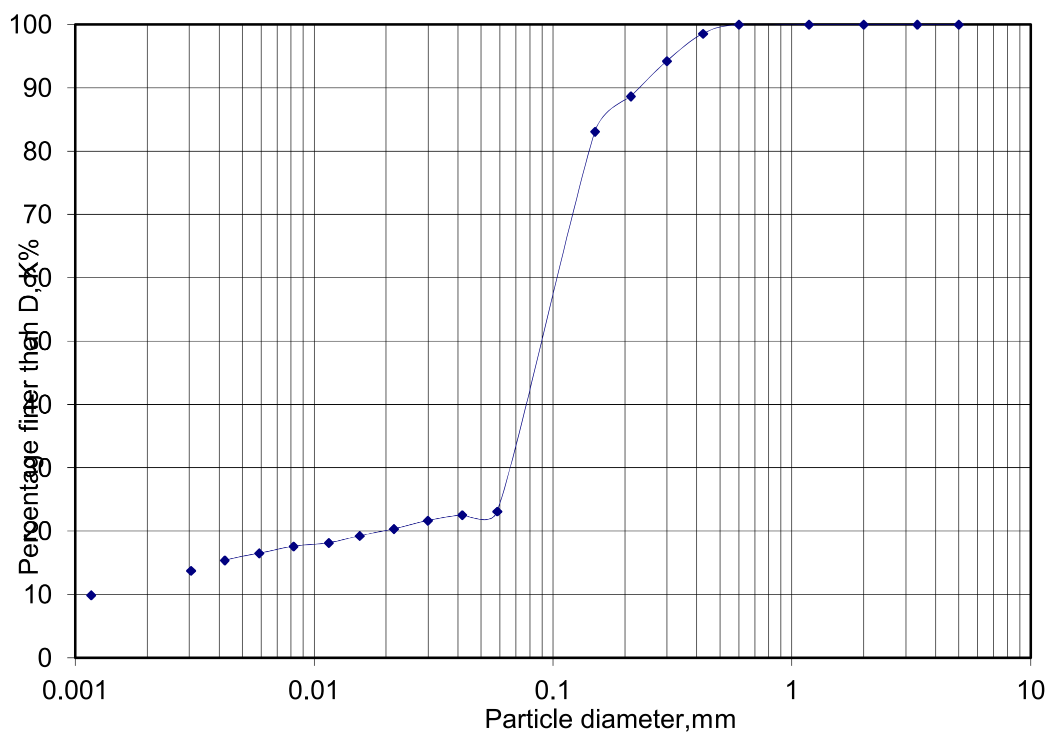

Figure 24: Sample 6 PSD

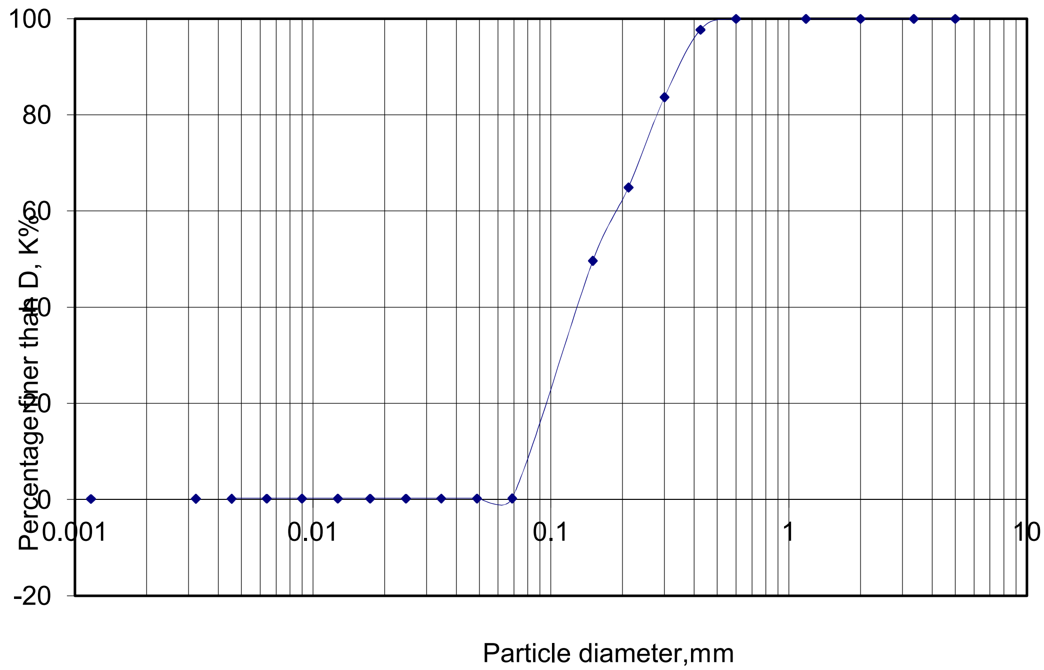

Figure 25: Sample 7 PSD

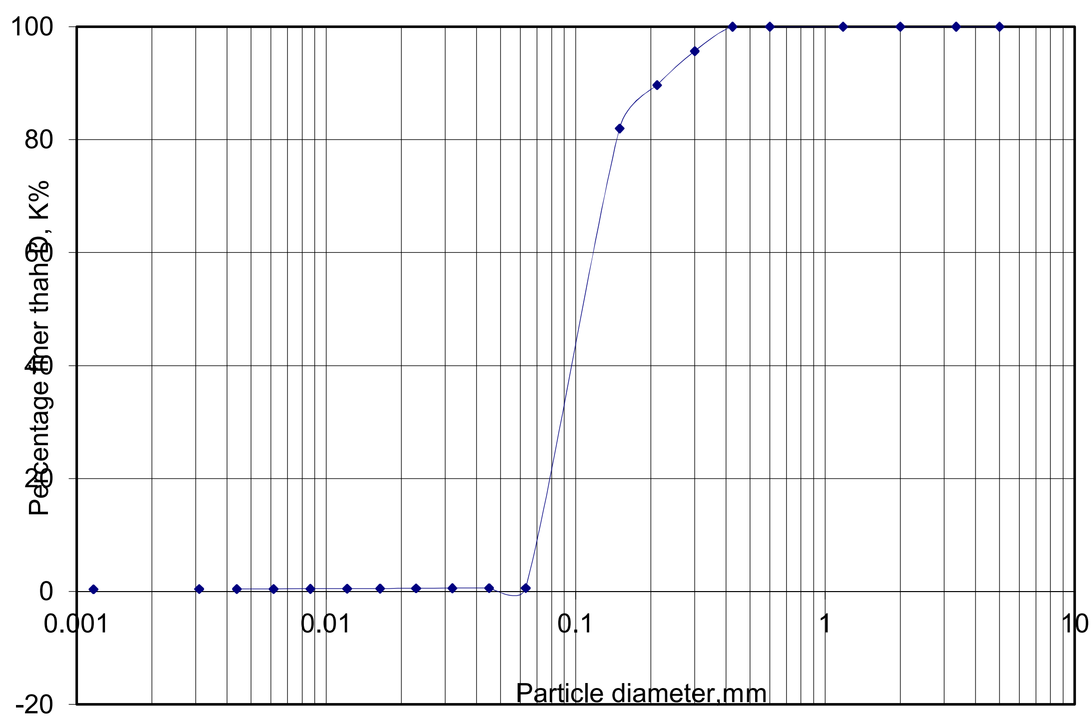

Figure 26: Sample 8 PSD

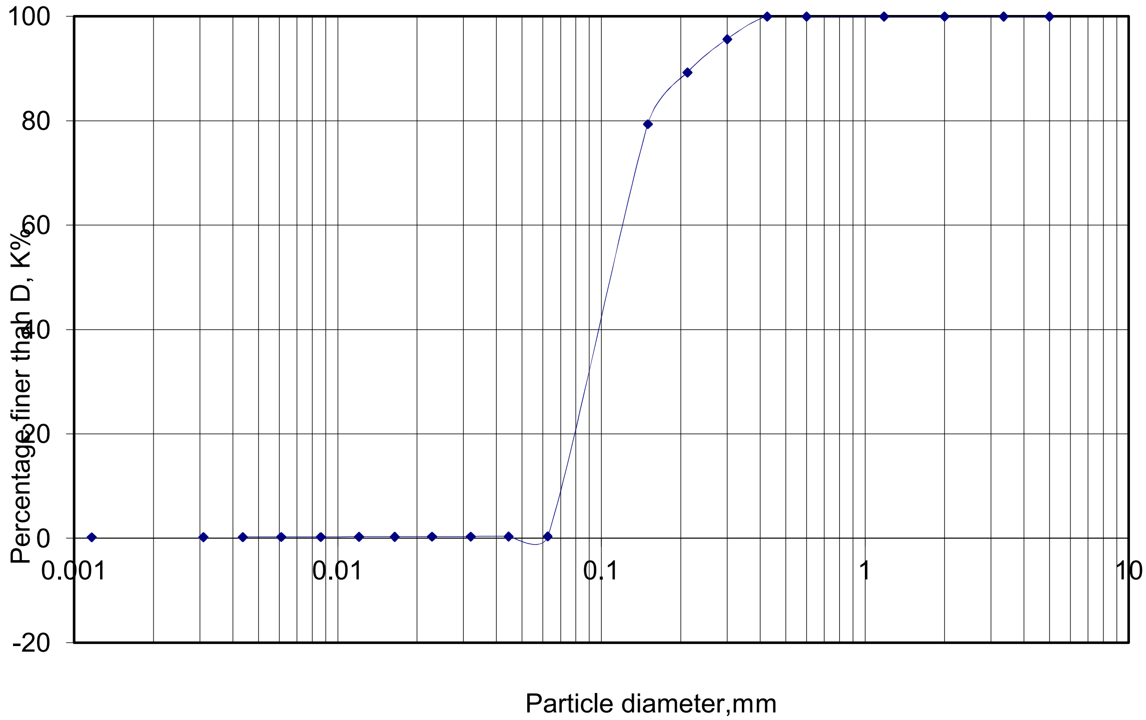

Figure 27: Sample 9 PSD

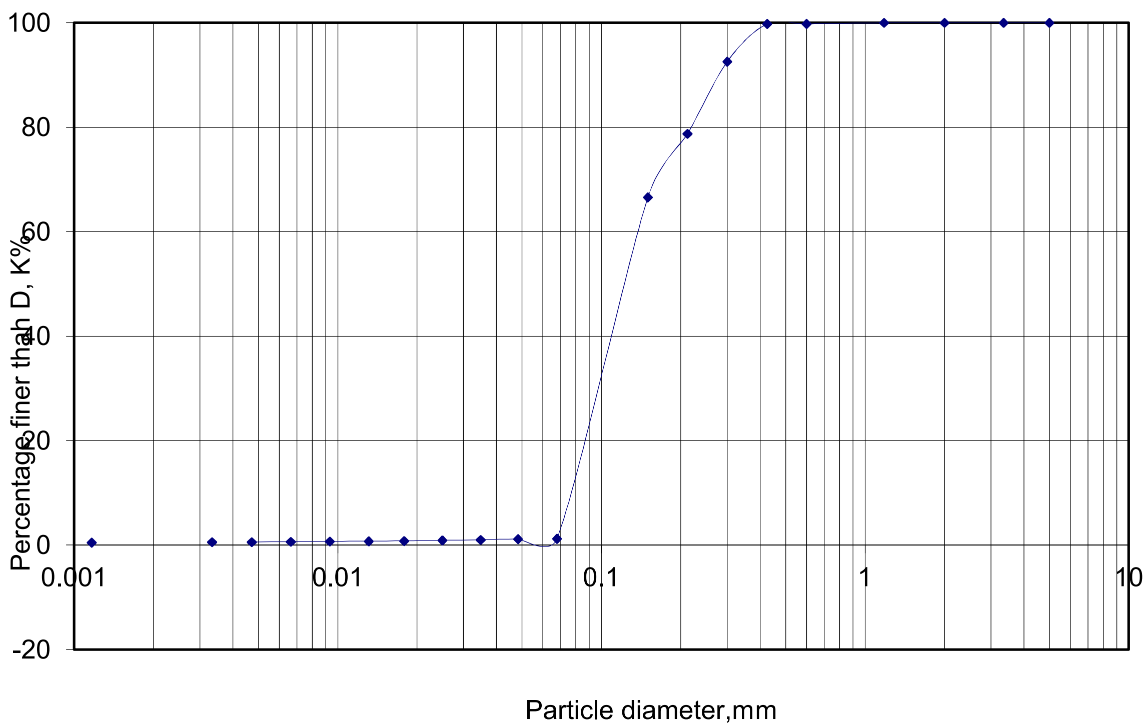

Figure 28: Sample 10 PSD

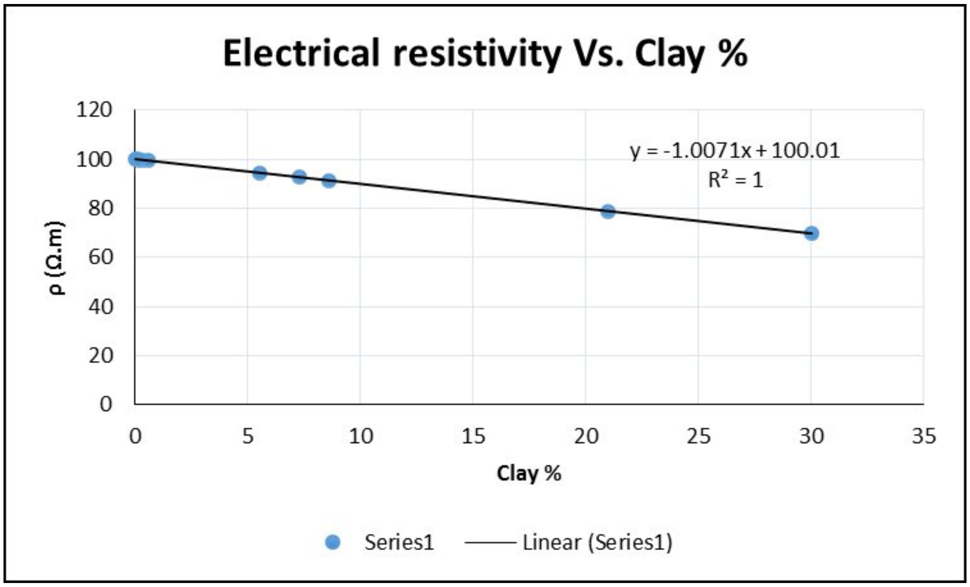

Figure 29: Electrical resistivity Vs. Clay percentage