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The Influence of Mineralogy and Cation Exchange Capacity toward Electrical Resistivity Value

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Abstract: Electrical Resistivity Tomography (ERT) is a method used for subsurface profiling in soil to characterize soil thickness, fracture zones, soil saturation, salinity and groundwater based on the electrical resistivity value (ERV). There are multiple factors that influence the electrical resistivity value, such as the porosity, degree of saturation, mineralogy, density, cation exchange capacity (CEC), and water resistivity. For this study, the effect of CEC towards resistivity value is studied via controlling the mineralogy factor, saturation, porosity and water resistivity. Thus, via understanding the CEC factor able to relate the resistivity and mineralogy of soil. This study is using a few common minerals in soil and rock, such as kaolinite, montmorillonite, illite, quartz, mica, and feldspar. The particle sizes of all tested minerals were passing 0.063mm sieve. The basic index properties of minerals such as particle size distribution, specific gravity, and Atterberg limit were tested. The instruments of Terrameter LS2 and resistivity box were used to determine the resistivity value of minerals. The Atomic Absorption Spectroscopy (AAS) machine was used to analyze the CEC of minerals via dilute with the ammonium acetate solution. The porosity and degree of saturation of minerals mixed with distill water were controlled between the range of 0.5 to 0.6 and 20% to 100%. The CEC of each mineral has different value, where the lowest and the highest minerals CEC in this study were Kaolinite and Montmorillonite at 1 and 70, respectively. The electrical resistivity values decrease with the increasing of CEC value and degree of saturation. The mineral that has higher CEC indicates lower resistivity value. Meanwhile, via increasing the degree of saturation of minerals were decrease its resistivity values.

Keywords: Electrical resistivity value, cation exchange capacity, mineralogy, porosity, saturation

1. Introduction

Groundwater exists in the interparticle pore spaces and the fractured rocks. This unseen water resources can be utilized for the water security for the nation that protecting people against drought. The groundwater contains and transmits in aquifer is usually determined by adopting a geophysical electrical resistivity tomography (ERT). However, interpretation tasks to decide the aquifer layer is unable to directly refer to the earth material-resistivity chart due to the

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overlapping values. Thus, it is important to understand the influence of the parameters towards the resistivity value. It is challenging to identify the sandy body for the groundwater aquifer in the Quaternary geological formation due to the ground is below the groundwater table. The ground is in saturated condition and thus resulting the resistivity value is lower for any particle size materials i.e. gravel to clay. The silt-clay layer is low permeable, thus not potential for aquifer. Thus, it is important to recognize the low permeability of silt-clay subsurface layered. The silt-clay is made of a few types of mineralogy, where each mineral has significant different value of cation exchange capacity (CEC). This study is designed to understand the factors that influent the resistivity value and soil properties such as mineral, CEC and degree of saturation. This research was conducted in the laboratory scale, which able to control the silt-clay variables. It is expected to improve the understanding of resistivity value and improve the earth material-resistivity chart. This information will help in the interpretation of the actual groundwater aquifer when dealing with the saturated earth materials especially in the Quaternary formation.

Electrical Resistivity Tomography (ERT) is a method used in interpreting site investigation for determination of soil thickness, variations in soil saturation, salinity intrusions, fractured rock zones and aquifer [1,2]. Resistivity value obtained from ERT is affected by particle size, porosity, mineralogy, concentration of ions within pore fluid and fluid resistivity [3,4,5]. In the saturated ground condition, it is challenging to interpret soil types in the saturated subsurface due to the domination of water resistivity. Hence, the resistivity value could be utilized to identify the changes in soil parameters within the saturated subsurface. Multiple site investigations studies have been conducted in relation towards the resistivity value of the subsurface. For this particular study however, the testing is performed in a lab scale environment where the important factors affecting the resistivity values are controlled.

The entire concept of resistivity logging is founded on a few fundamental equations that are introduced. The current flowing through a conductor I from point A to point B is proportional to the voltage V between point A and point B as shown in **Fig. 1**. Resistance value is determined by the type of materials ability to resists electrical voltage. However, if the sample length and size vary, the sample's resistance to the passage of current should also vary. Hence, the dimensions of the sample should be taken into considerations. By considering the resistance per unit length and area, the effect of the dimensions of the sample can be removed. The resistivity value obtained is based on the property of the material and not according to its dimensions. The resistance per unit length of an area is called the resistivity, ρ.

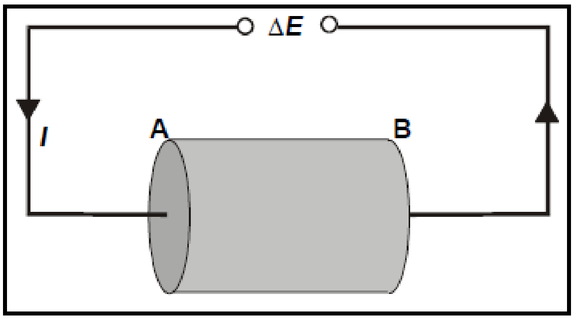

Fig. 1 - Schematic of current flow in a material

Archie has extensively shown the formation's resistivity relationships to the resistivity of the fluids saturating it, the porosity of the formation, and the fractional degree of saturation of each fluid present Archie's equations was an empirical equation which relates, for a clay free sediment, the electrical resistivity (ρ) of porous rock containing water and cement to the fraction of the pore space that is filled with water as shown in equation 1.

$$\rho = a\phi^{-m} {S_w}^{-n} \rho_w \tag{1}$$

Where, ρ_w is the resistivity of water, ϕ is the porosity, S_w is the water saturation of the sample, a is the tortuosity of the soil sample, m is the cementation of the mineral sample and n is the saturation exponent with the fix value of 2. This equation is not applicable for clay soils due to the clay's structure and its cation exchange capacity (CEC). However, with the use of Waxman and Smith (1968) which was derived from the original Archie's law model, the electrical conductivity of clay is proportional to the CEC in which is dependent on clay type, volume and distribution. The measured bulk conductivity is therefore dependent on the properties and distribution of clay [6]. CEC based model can be used to calculate as a theory as shown in equation 2.

$$\rho_o = (\phi^m \left(\beta \frac{Q_v}{S_w} + \frac{1}{\rho_w}\right) {S_w}^{n})^{-1} \tag{2}$$

Where, ρo is the clay sample resistivity, ϕ is the porosity, β is the counter-ion conductance which is a CEC dependent parameter (temperature), Qv is the counter-ion conductance which is a CEC dependent parameter, Sw is the water saturation and ρw is the water resistivity

Electrical resistivity values (ERV) of the subsurface are relatively influenced by variation of basic geotechnical properties related to soil such as moisture content. In a case study conducted by [7] the value of the same sample collected on the same site compromising of gravelly sand, shows that a sample with higher moisture content has a lower ERV as compared to the sample with a lower moisture content. A similar outcome was obtained in a case study conducted by [8] in which conducted six (6) month periods showing the difference resistivity value of the wettest condition is substantially lower compared to the driest condition. This shows that the presence of moisture content within a subsurface affects the resistivity value of the subsurface materials immensely.

The relative ability of soils to store cations, is referred to as cation exchange capacity (CEC). the clay particles have a net negative charge. Alteration mineral with a high CEC in clay minerals, favor the conduction of an electrical current between pore fluid and the pore wall of the rock [9,10]. The interface or surface conduction is caused by the highly mobile ions that form a conductive layer on the surface of the pore walls [11]. The mobility of ions is thereby related to the CEC of the mineral phase [9]. The higher the CEC of the clay mineral, the higher the interface conduction which shows that high electrical resistivity coincide with low CEC values, and low electrical resistivity values correspond to high CEC values [12]. This paper is to evaluate the influence of mineralogy and CEC toward the ERV.

2. Methodology, Equipment and Materials

Index tests was carried out to obtain moisture content (MC), liquid limit (LL), plastic limit (PL) and particle size distribution (PSD). All testing was carried out according to the British Standard (BS 1377:1990). Ammonium acetate is used in determining the CEC of the mineral samples. Ammonium acetate is a solution used to extract the cation present in the mineral sample such as calcium (Ca2+), magnesium (Mg2+) and potassium (K+) by electrostatic force. 100 mL of 1 M of ammonium acetate is mix with a 10 g mineral sample. The sample was filtered with filter paper that has been pre-washed with ammonium acetate. The filtered mineral was obtained in the liquid form with the volume of 100 mL and tested for the value of calcium (Ca2+), magnesium (Mg2+) and potassium (K+) with the Atomic Absorption Spectroscopy (AAS). The value of CEC is calculated in unit meq/100g as follows;

$$\frac{mg/L\,Ca^{2+}}{200} + \frac{mg/L\,Mg^{2+}}{120} + \frac{mg/L\,K^{+}}{390} = (meq/100g) \tag{3}$$

The resistivity test was performed using six types of minerals at different degree of saturation (0.2, 0.5 and 1.0) until completely saturated. The device used to measure the resistivity was Abem Terrameter LS2 and resistivity soil box. For the soil box, the 4-electrode method are used follow the ASTM G57 Standard and ASTM G187/AASHTO T-288 Standards respectively. To reduce the effect of particle sizes the materials used in the testing were in the form of silt and clay sizes. The Abem Terrameter LS2 was set to the maximum of 500 Volts and the maximum current generated at 200 Milliampere (Ma), with the minimum amount of 3 to 6 stacking of collected data. The ERT set-up is shown in **Fig 2.** Each dry mineral sample was weighted at 200 gram and mixed with distilled water. The sample was placed within the soil box and tap the sample using 500 gm rod at 10 blows for each layer. It was designed to three (3) layers to make the sample completely filled the soil box. The tested samples were tested its moisture content and density. The distilled water at resistivity value of 4000 Ωm was used to mix with the minerals.

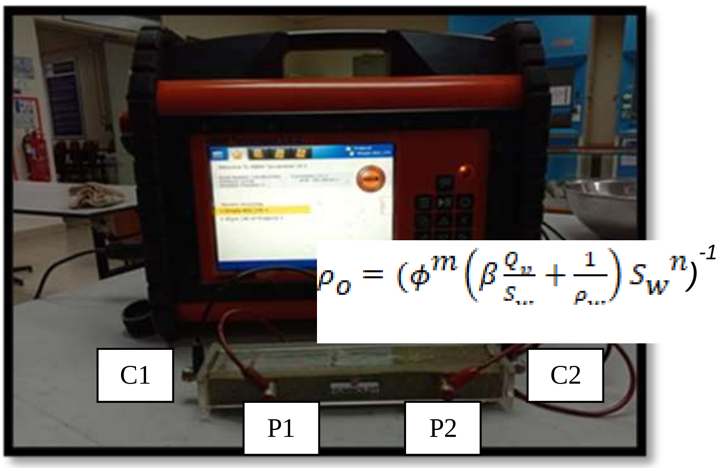

Fig. 2 - ERT set-up

The properties of the minerals use in this study are shown in Table 1 and Table 2. The samples were sieve passing 0.063 mm to obtain constant variable of particle size and to reduce the effect of the porosity of the samples. For the minerals CEC testing were mixed with ammonium acetate at pH 7 and were tested using the Atomic Absorption Sprectometer (AAS).

Table 1 - Physical properties of the mineral sample

Physical Properties	Kaolin	Illite	Montmorillonite	Quartz	Mica	Feldspar
Liquid Limit (%)	71.2	37.0	185.0	34.0	65.4	32.0
Plastic Limit (%)	36.6	22.4	55.1	Non- Plastic	35.9	26.6
Plastic Index (%)	34.62	14.63	129.95	-	29.5	5.42

Table 2 - Particle size distribution result for minerals

Mineral	Silt (%)	Clay (%)
Kaolinite	67	33
Illite	90	10
Montmorilonite	55	45
Quartz	82	18
Feldspar	91	9
Mica	63	37

3. Result and Discussion

The density and specific gravity for each mixed and mineral were obtained to calculated its porosity. The minerals at different water contents showed the porosity of all mixtures were from 0.5 to 0.6. The particle sizes of the mineral samples were in categories of silt and clay, thus the effect of particle size towards resistivity value can be eliminated. The CEC value for each mineral is tabulated in Table 2. The lowest to highest CEC values were kaolinite, feldspar, quartz, mica, and illite montmorillonite with the CEC value of 1, 2, 4, 30, 40, 70 meq/100g respectively. The result obtains had strong agreement with study conducted by [13] where the type of phyllosilicate in soil determines the value of CEC, namely montmorillonite and vermiculite which have a very high CEC value. Hence, soil containing these minerals are expected to have a high CEC value. However, soils with dominant kaolinite mineral content, such as granite residual soil are expected to have low CEC values

Table 2 - CEC value of clay minerals

Minerals	Cation Exchange Capacity, CEC meq/100g
Kaolinite	1
Feldspar	2
Quartz	4
Mica	30
Illite	40
Montmorillonite	70

Fig. 3 presented the plotting graph of resistivity, CEC versus minerals. The electrical resistivity value (ERV) with less, medium and fully degree saturation (0.2, 0.5 and 1.0) was plotted against CEC value for minerals of kaolinite, feldspar, quartz, mica, illite and montmorillonite. The result shows the trend of ERV for minerals kaolinite, feldspar, quartz, mica, illite, and montmorillonite. The electrical resistivity values decrease with the increasing of CEC value and degree of saturation. The mineral that has higher CEC indicates lower resistivity value. An increasing degree of water saturation from 20% to 100% shows a variation of ERV for Kaolinite and Montmorillonite from 5990 to 46 Ωm and 105 to 3 Ωm, respectively. The higher mineral CEC is due to the higher the interface conduction, thus lowering the electrical resistivity value.

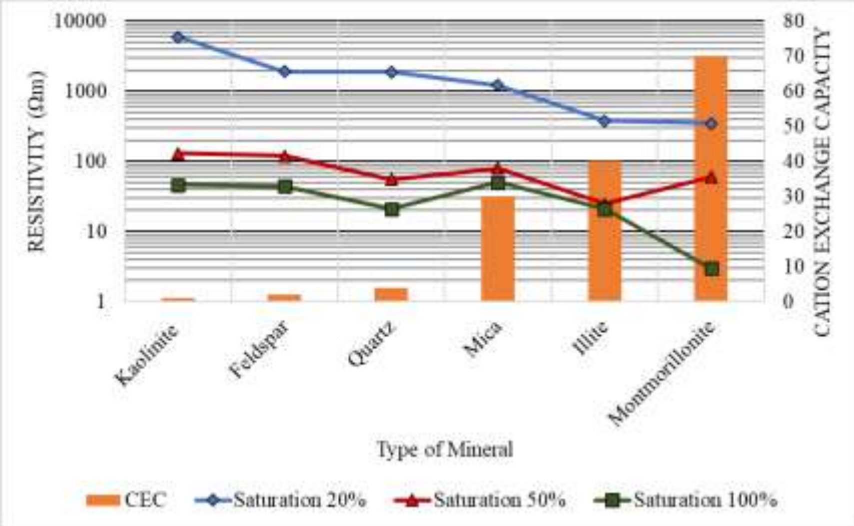

Fig. 3 - Electrical resistivity and cation exchange capacity relationship with minerals and degree of saturation

4. Conclusion

The factors that influence the electrical resistivity value stated in Archie's law are porosity, degree of saturation and water resistivity. For this study, the CEC effect the porosity in Archie's law. Meanwhile the CEC is controlling by the mineralogy. Thus, via understanding the CEC factor able to relate the resistivity and mineralogy of soil. The porosity and degree of saturation of minerals mixed with distilled water were controlled between the range of 0.5 to 0.6 and 20% to 100%. The CEC of each mineral has different value, where the lowest and the highest minerals CEC in this study were Kaolinite and Montmorillonite at 1 and 70, respectively. The electrical resistivity values decrease with the increasing of CEC value and degree of saturation. The mineral that has higher CEC indicates lower resistivity value. Meanwhile, via increasing the degree of saturation of minerals were decrease its resistivity values.

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