

**INVESTIGATING ELECTRICAL RESISTIVITY OF HIGHLY COMPACTED
BENTONITE AS A MONITORING OPTION FOR NUCLEAR WASTE
REPOSITORIES**

by

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Abstract

Bentonite clay is an essential component of the engineered barrier systems required around nuclear waste bundles in a deep geological repository (DGR). The bentonite is subject to both thermal and hydraulic gradients which may cause failure of the barrier system compromising the stability of the deep geological repository. Regular monitoring and evaluation of the condition of the highly compacted bentonite (HCB) is the key to the long term safe storage of nuclear waste bundles. The degree of saturation of the bentonite is the most critical parameter used to assess the performance of the material. The thermal and electrical resistivity of highly compacted bentonite samples were measured to develop a relationship based on the degree of saturation of the material. In addition, this research investigated the relationship between total suction and electrical resistivity.

Moreover, estimating the microbial activity near the waste bundles is a crucial part of the monitoring-process, because it can lead to microbial induced corrosion (MIC) and jeopardize the safety of the repository. The inherent physical characteristics of highly compacted bentonite, such as high swelling pressure and small pore size, reduce the microbial activity near the used fuel containers, which would reduce or eliminate the possibility of microbial induced corrosion. It is reported in the literature that the microbial activity in the bulk of compacted bentonite can be controlled if the emplaced compacted bentonite has a uniform dry density of more than 1.6 g/cm^3 and salt concentrations above 100 g/L for sodium and calcium chloride; these conditions ensure that the swelling pressure is higher than 2 MPa and it keeps the water activity and the average pore size lower than 0.96 and $0.02 \text{ }\mu\text{m}$, respectively. High salinity typically plays a vital role in suppressing the microbial activity in the compacted bentonite. As mentioned above, the electrical resistivity is a powerful tool to monitor the performance of repositories. Following the same procedure, the salinity of the highly compacted bentonite can be monitored by means of electrical resistivity to obtain a clear depiction of the microbial activity within the deep geological repository.

Preface

Portions of this study have been accepted in a peer reviewed journal and a conference; furthermore, portions will be submitted for possible publication in peer-reviewed technical journals in geotechnical engineering.

List of publications related to this thesis

A portion of Chapter 1, Chapter 3 and Chapter 4 have been accepted in the Journal of Hazardous, Toxic, and Radioactive Waste. Sepehr Rahimi and Sumi Siddiqua, 2017. “Relationships between degree of saturation, total suction and electrical/thermal resistivity of highly compacted bentonites”.

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List of Abbreviations

DGR	Deep Geological Repository
HCB	Highly Compacted Bentonite
MIC	Microbial Induced Corrosion
CFU	Colony Forming Units
DDL	Diffuse Double Layer

List of Symbols

M_T and C_R	Thermal equation multiplier (Equations 2.7,4.1 and 4.2)
M_S	Suction equation multiplier (Equations 4.3 and 4.4)
X, Y	Constant parameter (Equation 4.1)
X^1, Y^1	Constant parameter (Equation 4.3)
E_R and R_E	Electrical resistivity
ψ	Total suction
S_r	Degree of saturation
T_R and R_T	Thermal resistivity
R	Gas constant
T	Temperature
M_w	Molecular weight of water
ρ_w	Unit weight of water
RH	Relative humidity
a_w	Water activity
σ and E_C	Electrical conductivity
F	Fraction of sand and gravel in the soil sample

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Chapter 1: Background and Thesis Organization

1.1 Introduction

The current focus of the energy sectors worldwide is to recognize clean alternative sources of power generation. One such alternative power source is nuclear energy. A massive portion of electrical demands is met by nuclear power plants, globally. Despite its benefits, the technology produces radioactive nuclear waste that requires unique disposal mechanisms. Long-term isolation of spent fuel and high-level radioactive waste in a deep geological repository is the most preferable nuclear waste disposal option among the countries benefiting from nuclear energy.

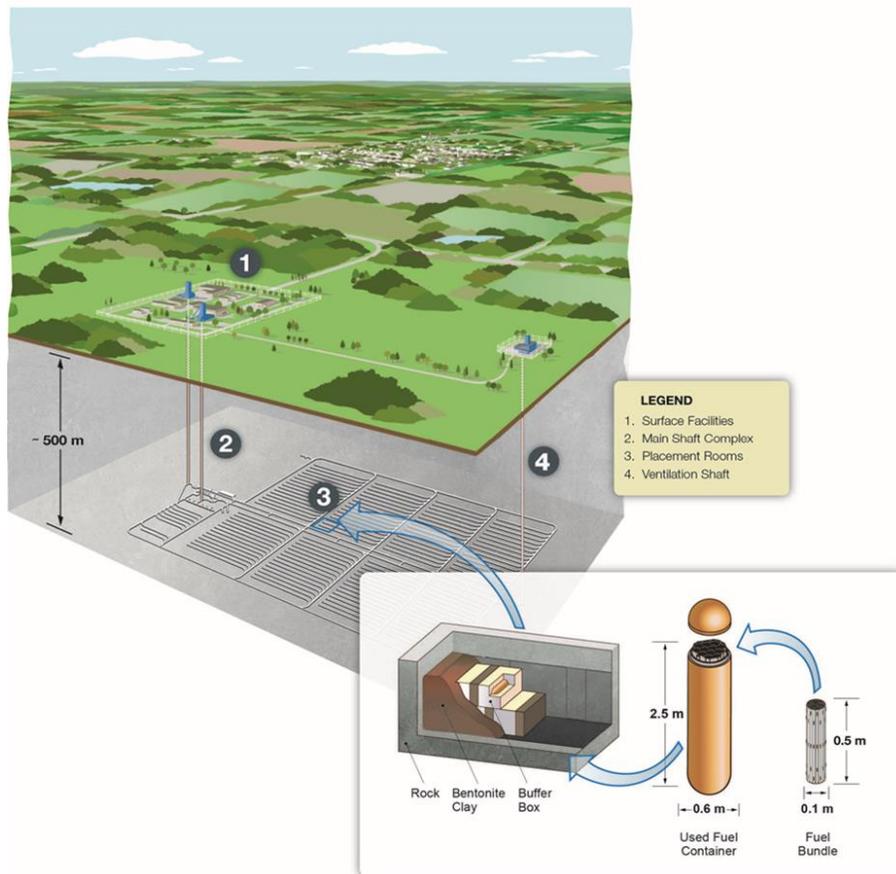


Figure 1.1 Deep geological repository concept. Adopted from NWMO (2016)

The typical layout of a deep geological repository contains a system of natural and engineered barriers which separates the waste bundles from the surroundings. Engineered barriers consist of several bentonite based materials. The favorable properties of bentonite that make it a strong candidate for producing engineered barrier materials are its microporous structure, low hydraulic conductivity, high plasticity and favorable sorption properties (Siddiqua et al., 2014; Tabiatnejad et al., 2016). These properties protect the waste bundles and restrict movement of the radionuclides in case of canister's failure.

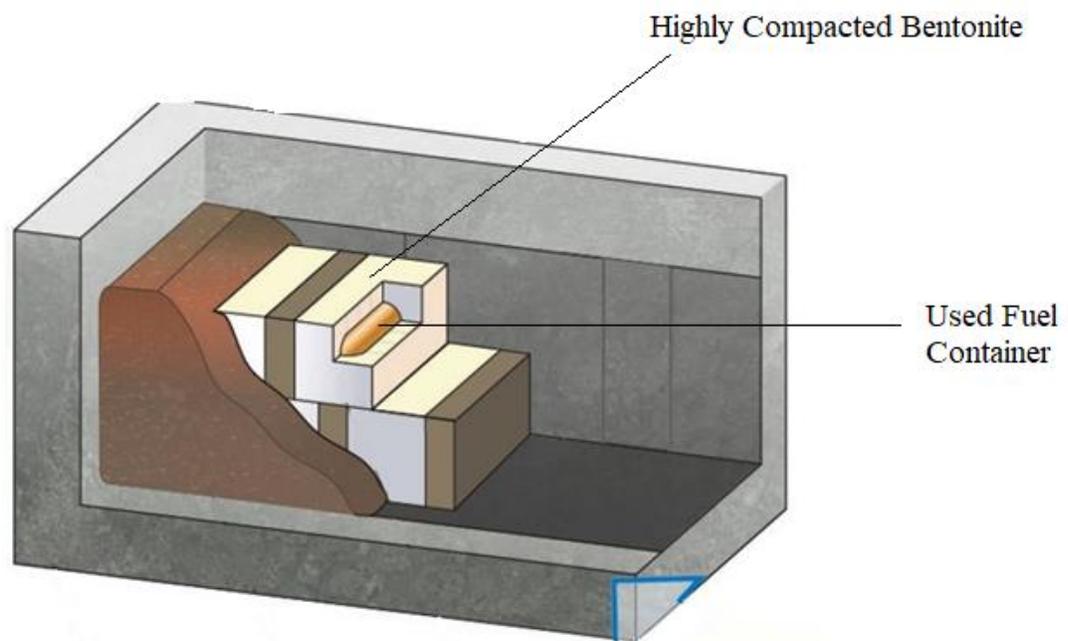


Figure 1.2 – Engineered barrier system. Modified from NWMO (2016)

Earlier research investigated the mechanical characterization of light and dense backfill materials (Siddiqua et al., 2011b) and their properties under the influence of pore fluid salinity (Siddiqua et al., 2011a, 2014; Sarkar and Siddiqua, 2016a, 2016b). To further enhance the knowledge on barrier materials, the current research was focused on highly compacted bentonite, which is one of the alternative barrier materials placed adjacent to the nuclear waste bundles.

During its life time, the deep geological repository typically undergoes several environmental processes depending on its location; Such as, heat generation due to waste decay over time, which elevates the temperature of the waste bundles. The generated heat gradually gets transferred into the surrounding barriers (Tabiatnejad et al., 2016). In addition, the ground water from the surrounding rocks flow into the system causing the compacted bentonite to expand and ensure proper sealing which is one of the key elements of the safety of a deep geological repository. Thus, there will be a moisture outflow from barriers closer to higher temperature to lower temperature region and inflow of moisture from external barriers to the center of the repository (Siddiqua et al., 2014). After closure, based on the location of the repository, it also experiences other processes, including freezing, gas dissolution, bentonite interaction with metal corrosion products, microbial effects (Sellin and Leupin, 2013). These processes must be assessed carefully to prevent potential damage to the waste bundles and the barrier system.

1.2 Motivation and objectives

To verify the performance of the deep geological repository in the long-term or at the time of the repository's evolution, it is essential to provide a monitoring program to evaluate the performance of the repository. The development of this monitoring program should take place at the same time as the repository's evolution. The purpose of this monitoring program is to warrant the safety of the repository (NWMO, 2012). The motive for this thesis is to develop a new monitoring method to evaluate the performance of the repository by means of electrical resistivity measurements. To this end, the following specific objectives are defined:

- Developing correlation between thermal/electrical resistivity, total suction and degree of saturation for highly compacted bentonite.

Deliverable: It has been suggested that these correlations can be used to measure the in-situ degree of saturation the highly compacted bentonite at the repository's environment.

- Establishing a relationship between electrical resistivity and degree of saturation at the presence of pore fluid salinity for highly compacted bentonite.

Deliverable: Results will provide a new method to measure the pore fluid's salinity of the deep geological repository.

- Establishing a relationship between electrical resistivity, pore fluid salinity and microbial activity for highly compacted bentonite.

Deliverable: A new potential practical guideline will be provided to estimate the microbial activity of the deep geological repository with the help of electrical resistivity measurements.

1.3 Thesis framework

This research thesis is comprised of five chapters. Chapter 2 reviews the background research conducted on the electrical properties of soils and the relationship between the electrical resistivity/conductivity with other soil properties. This chapter also reviews the microbial studies on the deep geological repository. Chapter 3 and 4 form the main body of this research. Chapter 3 presents the material and methods. Chapter 4 is devoted to characterization of electrical resistivity of the highly compacted bentonite and its relationship with thermal resistivity, total suction and salt concentration. In this chapter, the relationship between salinity and highly compacted bentonite's electrical resistivity is used to estimate the microbial activity at the deep geological repository. Finally, Chapter 5 summarizes the main findings of the thesis and outlines recommendations for future work.

Chapter 2: Literature Review

2.1 Electrical studies on soils

Due to the complex nature of soil, determining properties such as salinity, grain size, water content, and thermal resistivity requires expensive and time-intensive soil surveys. Furthermore, extensive laboratory experiments are often required to fully understand these soil parameters. One option to evaluate these properties in a cost and time efficient manner is to estimate them using soil electrical properties. Geo-electrical methods of testing are beneficial because they can provide a quick picture of the soil electrical properties from the surface to large depths without disturbance. These methods seem promising, since the electrical properties of soil such as electrical resistivity or conductivity can be used to estimate other soil properties through established correlations (Pozdnyakova, 2016). Geo-electrical methods offer solid and non-destructive measurements of subsurface properties, which has been used in several applications such as landfill contamination detection and oil surveys. Schlumberger (1912) first introduced geo-electrical methods, in which he demonstrated that subsurface rock bodies can be studied using electrical resistivity measurements. These concepts were first applied by oil companies in detecting petroleum reservoirs. Since then, an interest in determining subsurface soil properties via electrical measurements has grown steadily. An example of which can be seen in the study conducted by Ekwue and Bartholomew (2011), where the authors discussed the relationship between peat content and the electrical conductivity of the compacted soils in a laboratory environment. Soil properties, such as saturation, thermal resistivity, and bulk density are of crucial value in soil science and can also be determined through electrical measurements.

In this section, previous published correlations between the aforementioned properties and electrical resistivity are reviewed. Furthermore, the phenomenon that occurs when soils are under electrical current flow is discussed.

2.2 Theory of electrical flow in soils

Arulanandan and Smith (1973) and Mitchell (1993) reported that electricity is conducted through soil systems in a three-phase manner, where the paths through the sample are shown in Figure 2.1. The first path represents the flow of electrons through both conducting soil particles and the pore fluid in series. The second path is the flow solely through the pore fluid, and the last electrical path is solely through solid soil particles that have close contact with each other. With this in mind, it can be identified that the total electrical flow depends on soil type, soil structure, pore fluid, and the degree of saturation (Mitchell, 1993; Lesmes and Friedman, 2005; Jung and Asce, 1900).

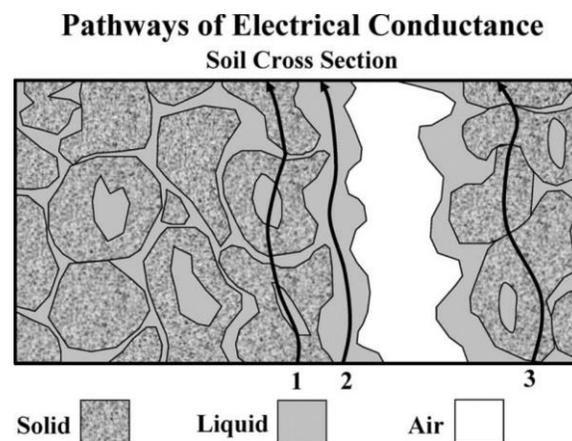


Fig 2.1 Electricity pathways in a porous media. Adopted from Corwin and Lesch, (2005)

It is assumed that clean sand grains are relatively non-conductive and as a result, the pore fluid is the dominant path for electrical flow which makes the void ratio, granular skeleton, and degree of saturation crucial factors in this matter (Santamarina et al., 2001; Mitchell, 1993; Jung and Asce, 1900).

In clayey soils, the mineral surfaces are negatively charged; therefore, when they are in contact with an electrolyte, this negative charge is balanced by the mobile ions within the electrolyte. To reach a state of equilibrium, the ions absorbed by the negative mineral surface charge must diffuse, thus shaping the *electrical diffuse layer*. Water fills the gaps between the electrical diffuse layer and the mineral's surface forming the *stern layer*. The stern and the diffuse layers form the *diffuse double layer*. Electrical conduction through the diffuse double layer can contribute considerably to the total electrical conductivity of the porous medium. This type of conduction is known as the surface conductivity (Revil and Glover, 1997).

2.3 Relation of electrical resistivity with other soil properties

In the following subsections, the relationship between electrical resistivity and other soil properties is reviewed.

2.3.1 Water content

Water content is a key factor which determines the ability of a soil to transmit electrons. Resistivity is characterized as the strength of a material's opposition to the flow of electrical current; and in soils, this property is governed in large part by water content (Abu-Hassanein et al., 1996a). Water content is important because when the soil is subject to electrical potential difference, the ions migrate through the soil solution through the soil pore network (McCarter, 1984). The electrical conductivity can therefore be correlated to the water content.

At low water contents, the electrical resistivity decreases significantly as the water content increases; whereas at high water contents, increasing the water content further yields slight increase in electrical resistivity (Abu-Hassanein et al., 1996a). The point at which this inflection occurs was found to be the optimum water content of the soil (Zha et al., 2006). The explanation for this phenomenon is that at low water contents, increasing the amount of water in the voids of

a soil improves the bridging between particles and facilitates easier flow of ions, thus decreasing its electrical resistivity. However, at the optimal water content, the soil structure has reached a sufficient level of continuity (Zha et al., 2006) and the further increase in the amount of water will not significantly improve the ability of ions to travel through the medium. For sand and gravel materials, conductance occurs primarily in the liquid contained within the soil; whereas with clay based soils; conductance occurs in the liquid contained within the soil as well as on the surfaces of the clay particles (Abu-Hassanein et al., 1996a).

2.3.2 Degree of saturation

It is important to take into consideration the fact that two different soil samples may have the same water content but different degrees of saturation due to compaction. For this reason, water content alone cannot be the only basis for the prediction of the soil electrical resistivity; rather, it is a function of water content as well as degree of saturation (McCarter, 1984). Therefore, McCarter (1984) used the fractional volume of water as the controlling factor as it is defined as the fraction of water in a sample to the whole volume of the sample. This means that either an increase in water content or reduction in pore void volume will result in a higher degree of saturation and therefore a lower electrical resistivity.

The electrical resistivity of clays under different degrees of saturation was examined and the results showed that at a certain degree of saturation the electrical resistivity is at its lowest. This can be explained by considering the rule of diffuse double layer (DDL); in that saturation state, diffuse double layer is fully developed, which means that the electrolyte contribution in electrical conduction is at its highest. Going beyond that saturation, demineralization happens which means the ions are disturbed and will not function properly in electrical conduction. On the other hand, below that certain degree of saturation, the introduction of a third phase occurs; which is the

gaseous phase that increases the electrical resistivity of the sample (Macha et al., 2004; Mojid and Cho, 2006).

2.3.3 Modelling

In order to predict the electrical behavior of a porous soil media containing water, various models have been established to describe the phenomenon. One of the earliest models is a three-resistor model proposed by Wyllie and Southwick (1954), which represents a saturated soil as three resistive elements in parallel (Wyllie and Southwick, 1954). The resistive elements are:

- Particles in electrical contact with each other
- The electrolyte within the pore void space
- Particles and electrolyte in series with each other

These elements can be mathematically represented as shown in equation 2.1, where σ_0 = conductivity of formation, σ_r = conductivity of rock matrix, σ_w = conductivity of electrolyte, and W, X, Y, Z are geometrical factors.

$$\sigma_0 = \frac{\sigma_r \sigma_w}{W \sigma_r + Z \sigma_w} + X \sigma_r + Y \sigma_w \quad (2.1)$$

However, Bussian (1983) suggested that equation 2.1 is deficient because the geometrical factors are difficult to obtain accurately. Another method developed by Waxman and Smits (1968) included a two-resistor model, and has become the most widely accepted method. One of the two resistive elements in this model represents the pore water in the void space of the soil, and the other represents the resistance associated with clay particles (Waxman and Smits, 1968). This model assumes that that the current attributed to the clay exchange ions and the current attributed

to the electrolytic ions follow the same path through the formation (Bussian, 1983). The mathematical representation of this model is shown in equation 2.2.

$$\sigma_0 = X\sigma_r + Y\sigma_w \quad (2.2)$$

The Waxman and Smits model is only able to predict the conductivity of a sample that only has one type of electrolyte, so an alternative method known as the dual water method was proposed by Clavier et al. (1977). This model is similar to the Waxman and Smits model, but it describes the geo-electrical behavior by assuming that two kinds of water are present. The first kind of water is called clay water and represents the clay particles, and the other water represents the water that exists within the soil voids.

2.3.4 Compaction effort

Kowalczyk et al. (2014) indicated that soil electrical resistivity tends to decrease as the degree of compaction increases. This trend is more prevalent in soils with higher clay contents (Filho et al., 2015). Higher compaction effort will yield a greater bulk density, closer particle contacts, and a smaller void ratio; this creates a more interconnected water phase by expelling the gaseous phase. Therefore, the absence of the non-conductive phase will decrease the electrical resistivity of the soil (Ekwue and Bartholomew, 2011; Alakukku, 1996; Richard et al., 2001; Pereira et al., 2007; Nakshabandi and Kohnke, 1965).

Abu-Hassanein et al. (1996a) discussed the effect of compaction on the electrical resistivity of clays. According to this study, compaction dry of optimum often leads to higher electrical resistivity. This could be due to the structural changes that could be experienced during the compaction phase. When compacting at dry of optimum, clay clods are not fully remolded which will form larger pores. Larger pores lead to a greater gaseous phase and partially developed diffuse double layer (Acar and Oliveri, 1990; Benson and Daniel, 1990; Lambe, 1958). On the contrary, in the case of compacting wet of optimum, there is a higher particle to particle contact and smaller saturated pores will form which will lead to a lower soil electrical resistivity (Benson and Daniel, 1990).

2.3.5 Porosity

The relationship proposed by Archie (1942) relates the resistivity of a saturated soil (ρ) to the resistivity of its pore fluid (ρ_w). Since the electrical resistivity of a soil is affected mainly by its water content, it is therefore more sensitive to the properties of the pore fluid itself. This relationship is shown in equation 2.3, where n is porosity and a and m are empirical constants that depend on the type of soil (Abu-Hassanein et al., 1996a). This equation is generally known as Archie's law.

$$\rho = a\rho_w n^{-m} \quad (2.3)$$

This relationship indicates that the resistivity of a saturated soil is dependant on its porosity and pore fluid resistivity, as well as the physical structure of the soil fabric. As the porosity increases, the ions can flow more freely through the soil and resistivity decreases (Dijkstra et al., 2012; Rinaldi and Cuestas, 2002). Archie's law was further enhanced by Shah and Singh (2005) which considered both saturated and unsaturated soil conditions.

2.3.6 Temperature

Changes in temperature cause multiple changes in soils; firstly, temperature alters the viscosity of the electrolyte, and as a result, it changes the mobility of the ions through the medium (Abu-Hassanein et al., 1996a). It is also capable of modifying water distribution of the medium, both of which will alter the soil's electrical resistivity (Nouveau et al., 2016). Equation 2.4 was suggested by Rinaldi and Cuestas (2002) and Abu-Hassanein et al. (1996a) to estimate soil electrical resistivity at relatively low temperatures.

$$\rho T = \frac{\rho 18}{1 + \alpha(T - 18)} \quad (2.4)$$

Where ρT is the soil's electrical resistivity at the desired temperature, $\rho 18$ is the measured electrical resistivity at 18°C, and α is an empirical parameter having a value around 0.025°C⁻¹. Having a relationship estimating the effect of temperature on the soil electrical resistivity is of significant importance, because the temperature may vary between sampling locations and therefore must be corrected.

When the temperature increases, the electrical resistivity of the pore water decreases due to the decrease in the viscosity of the water as well as a surge in the molecular agitation, causing lower soil electrical resistivity (Samouelian et al., 2005; Rinaldi and Cuestas, 2002; Abu-Hassanein et al., 1996a). At elevated temperatures, water content may decrease significantly, resulting in an increase in the soil electrical resistivity. Consequently, when soils are submitted to elevated temperatures, there is a competition between the two opposite effects of temperature on soil electrical resistivity leading to soil electrical resistivity stabilization. Beyond a certain temperature, the soil sample may lose a large quantity of its water due to water evaporation, which normally results in a rise in the soil electrical resistivity (Nouveau et al., 2016).

2.3.7 Thermal resistivity

Thermal resistivity is a measure of the resistance offered by the soil to the passage of the heat through it. Through soils, heat is transferred mainly through convection in the electrolyte. Thus, the soil electrolyte constituent is the main medium for electrical current as well as heat transfer. Regarding this fact, researchers have investigated possible relationships between these two resistivities. Singh et al. (2001) examined different soil thermal and electrical resistivity properties, where soils were categorized based on their fractions of sand and gravel. For the sake of comparing the electrical and thermal resistivity of these soils, they were plotted on a log-log scale against the degree of saturation. Equations 2.5 and 2.6 are proposed from the trends of these log- log plots.

$$\text{Log}(R_E) = C_1 - C_2 \text{Log}(S_r) \quad (2.5)$$

$$\text{Log}(R_T) = C_3 - C_4 \text{Log}(S_r) \quad (2.6)$$

Where R_E is in ohm.cm , R_T is in degree centigrade.cm per watts, S_r is the degree of saturation and C_{1-4} are constants. By combining these two equations, a general relationship can be governed:

$$\text{Log}(R_E) = C_R \text{Log}(R_T) \quad (2.7)$$

Where C_R is a multiplier. If the sum of gravel and sand is represented by F (percentage), the soil samples reported by Singh et al. (2001) had a C_R of :

$$C_R = 1.34 + 0.0085 \times F. \quad (2.8)$$

Sreedeeep et al. (2005) perfected equation 2.7 by incorporating the effect of saturation on both thermal and electrical resistivity. This is represented by another multiplier which is a function of both saturation and the fraction of sand and gravel in the specimen.

$$C_R = X + Y \times e^{(-S_r \times Z)} \quad (2.9)$$

$$X=1.1+ 0.01\times F \quad (2.10)$$

$$Y=0.9 - 0.01\times F \quad (2.11)$$

$$Z=0.02+0.0006\times e^{(F/25)}. \quad (2.12)$$

Erzin et al. (2010) developed an artificial neural network (ANN) model to come up with a correlation which relates these two resistivities, where the input parameters are the soil type and the degree of saturation. There are two proposed ANN models, one having F (soil type parameter) as the variable, and the second model brings both the soil type parameter and saturation into account. It is noted that the values predicted from the ANN models match the experimental values at a higher accuracy than those obtained from previous models.

2.3.8 Hydraulic conductivity

Measuring the hydraulic conductivity of soils is an elaborate and time-consuming process, which encourages the estimation of hydraulic conductivity through possible relationships with its electrical resistivity. Electrical resistivity tests, on the other hand, are promising alternatives because they offer quick and reliable databases. Researchers have tried to relate these two soil properties, but some of the efforts could not demonstrate a clear relationship between these two parameters such as the study conducted by Abu-Hassanein et al. (1996a). Alternatively, Rinaldi and Cuestas (2002) suggested a regression model which correlates the porosity and hydraulic conductivity as follows:

$$K=bn^g \quad (2.13)$$

In which K is hydraulic conductivity and n being porosity. The other parameters are constants that depend on the soil type. As mentioned previously, Archie's law is a relationship between electrical resistivity and porosity. Combining these two equations yields a relationship for hydraulic

conductivity based on electrical resistivity. Rinaldi and Cuestas (2002) emphasized that this equation is valid for pore fluids with medium to high salt concentration.

In addition to the above studies, there have been few other studies attempting to describe this problem. Niu et al. (2015) developed a theoretical hydraulic-electrical conductivity relationship using the 'bundle of capillary tubes' model. This model was tested on unsaturated soils and was strongly influenced by the tortuosity factor. Hydraulic conductivity modeling of coarse-grained soils using the results of electrical conductivity measurements was completed by Choo et al. (2016). The results of this study demonstrated that both electrical and hydraulic conductivity can be determined primarily through the porosity of soils, reflecting the fact that the pore spaces between particles is the main path for both electrical and hydraulic conduction. In another study conducted by Di Maio et al. (2015), a combined use of Archie's and van Genuchten's laws was proposed to predict the hydraulic conductivity of unsaturated soils using electrical resistivity measurements.

2.3.9 Salinity

Measuring the amount of salt in the soil is an important soil parameter in the agricultural related activities, and one of the earliest applications of the concept of electrical conductivity in soils. A method of measurement using a hard rubber tube with two electrodes to measure the conductivity of a soil paste (EC_p) was first described by Whitney and Means (1897). Later, tables were created by Davis (1927) and Davis and Bryan (1910) which correlate values of electric conductivity to corresponding total salt contents. This method was widely used because of its ease, speed, and reproducibility of results; making it possible for simple and accurate tests in field.

Rhoades et al. (1989) suggested that the amount of dissolved salts in a solution determines its ability to conduct electricity; and therefore, it is more effective to measure the electrical

conductivity of a soil paste extract (EC_e) to obtain a correlation with salinity rather than to measure the soil paste itself. A soil paste extract is prepared by mixing distilled water into a soil sample and letting sit for at least one hour, allowing for the salts in the soil to fully dissolve into the water which is then extracted from the paste and measured. Despite its higher accuracy, this method is a more time consuming and requires a laboratory environment to perform which may make it less favorable. Rhoades et al. (1989) published a correlation between the EC_p and EC_e , where EC_s is surface conductance, θ_s and θ_w are the volume fractions of solid particles and total water in the paste respectively, and θ_{ws} is the volume fraction of water in the paste that is coupled with the solid phase to provide an electrical pathway through the paste (Rhoades et al., 1989).

$$EC_p = \frac{(\theta_s + \theta_{ws})^2 EC_e EC_s}{(\theta_s) EC_e + (\theta_{ws}) EC_s} + (\theta_w - \theta_{ws}) EC_e \quad (2.14)$$

Shirokova et al. (2000) presented a table that was published by the Food and Agriculture Association of the United Nations that proposed an empirical factor K that can be used to correlate EC_e with various water to soil sample ratios. This method generally allows for easy electrical conductivity testing, and suitable for use in the field which would yield an accurate soil salinity reading.

2.4 Electrical resistivity of bentonite

Bentonite is a swelling clay that is used in an extensive range of applications. The focus of this section is to discuss the electrical properties of this clay. As mentioned previously the diffuse double layer (DDL) of clays (or bentonite) will increase its electrical conductance significantly (McNeill, 1980; Revil and Glover, 1997; Kibria and Hossain, 2014; Mojid and Cho, 2006; Weiler and Chaussidon, 1968). Along with other factors that affect the electrical properties of clays, cation exchange capacity contributes significantly to its electrical conductance. Those clays with swelling ability have the highest amount of cation exchange capacity (Kaufhold et al., 2015).

The importance of bentonite in many applications urged researchers to try different methods to determine the content of bentonite in a soil/slurry sample. One of the common methods was methylene blue test which was based on titration assessments (Alther, 1983). Since titration assessments are subjective and time-consuming; thus, researchers tried new methods to estimate the bentonite content of soils /slurries, one of such methods is the electrical resistivity test. In this method, the slurries were air-dried and their bentonite content was determined. Bentonite concentration and bentonite content are related by the following equation:

$$BC (\%) = \frac{C_B}{M_S} \times 100 \quad (2.15)$$

BC is mass of dry bentonite/mass of dry solids (%). C_B is the concentration of bentonite (kg/L) in the slurry. M_s is the mass of dry soil-bentonite mixture used to prepare the 1 L of slurry.

On the other hand, the relation between bentonite's concentration and electrical conductivity is:

$$\sigma_s = 0.065 + 2030 C_B \quad (2.16)$$

σ_s is the electrical conductivity (mS/m) of the slurry (Abu-Hassanein et al., 1996b).

Other than estimating bentonite's concentration, researchers tried to model the electrical conductivity of bentonite. Lima et al. (2010) suggested the series and parallel model. In this model, the current transport is considered to take place in two separate systems (parallel and series systems). The parallel system is affected either by the bulk solution or the surface of bentonite particles. On the contrary, the series system implies the alternate transport of current through both bulk solution and the surface of bentonite's particles. Lima et al. (2010) also suggested a third current transport path which is the conduction through the solid particles. This type of conduction takes place when the sample is well compacted, which causes the clay particles to be in a close contact, creating an overlapping diffuse double layer. Figure 2.2 shows the series and parallel models.

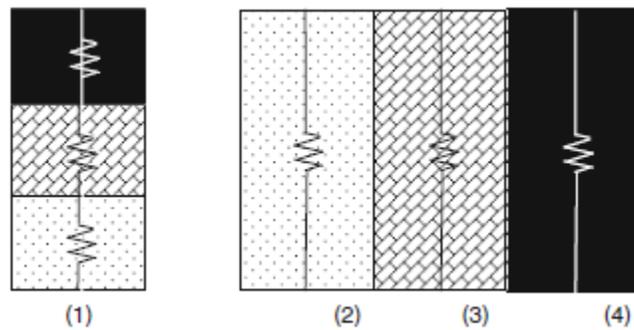


Fig 2.2 Series (1) and parallel (2-4) electrical transport of bentonite represented graphically. (1) transport in series through bulk/surface and solid phases, (2) bulk solution, (3) surface interface, (4) solid. Adopted from Lima et al., (2010)

2.5 Microbial studies on the deep geological repository

During its life time, the deep geological repository will undergo several environmental processes depending on its location; these processes must be assessed carefully to prevent potential damage to the waste bundles and the barrier system. One of such processes is the microbial induced corrosion (MIC) which is caused by the microorganisms existing at the repository. Microorganisms are categorized either as aerobic or anaerobic. During the repository operating phase, aerobic conditions will prevail; on the other hand, anaerobic conditions are anticipated once the trapped oxygen has been consumed which mainly happens when the repository has been closed (Sellin and Leupin, 2013). Anaerobic period will last several thousands of years. Microorganisms are active in the form of biofilms at the deep geological repository (King, 2009). Microbial biofilms develop on all surfaces in contact with aqueous environments (Little and Wagner, 1996). These biofilms are mainly composed of immobilized microorganisms embedded in an organic polymer matrix containing heavy metals, inorganic particles and cellular constituents (Characklis and Marshall, 1990). The biofilm has a time-dependent heterogeneous chemical and microbial nature (Videla and Herrera, 2005). Development of a biofilm may lead to the formation of chemical concentration cells, production of several corrosion intensifying materials (e.g. acids, ammonia and sulfide) and the presence of chemical catalysts, such as enzymes and so forth; all of these will play a specific role in the microbial corrosion phenomena (King, 2009; Little and Wagner, 1996). The term microbiologically influenced corrosion (MIC) is used to designate corrosion due to the presence and activities of microorganisms within biofilms; it also includes corrosive microbial metabolites that may be produced in one location and diffuse to the corrosion site (Féron and Crusset, 2014). Microorganisms grow, reproduce, and form colonies that are physical anomalies, resulting in generation of local anodes and cathodes which will form differential aeration cells leading to localized corrosion (King, 2009; King et al., 2013; Little and

Wagner, 1996). Furthermore, it is possible that the microorganisms' activity could produce oxidants, stimulate rates of partial reactions in corrosion processes or alter corrosion mechanisms (King, 2009; Little and Wagner, 1996; Videla and Herrera, 2005; Stroes-Gascoyne and Sargent, 1998). There is an increasing evidence that microorganisms exist and flourish in unlikely environments, including radioactive and nutrient-deficient waters and deep subsurface environments (Stroes-Gascoyne and West, 1997; Stroes-Gascoyne et al., 2010; King, 1996).

The presence of microorganisms solely does not threaten the safety of the nuclear waste bundles; for microbial induced corrosion to occur, these microorganisms must be active (NWMO, 2014). In general, the deep geological repository is an inhospitable environment for microorganisms (Little and Wagner, 1996). Based on the literature, microorganisms survive mainly as spores which do not contribute to microbial induced corrosion (Jalique et al., 2009). On the other hand, it is always possible to identify microorganisms that have adapted to survive even in extreme conditions. Factors that influence the development of microorganisms on or around nuclear waste bundles include existence of water, availability of energy sources, bentonite's dry density and its correlated swelling pressure, radiation, temperature, mass transfer and salinity (Stroes-Gascoyne and West, 1997). The summary of several studies regarding the effects of these factors on microbial activity is described in the following sections.

2.5.1 Water activity

In compacted soils and aqueous systems, the availability of water for microorganisms' growth is represented by water activity (a_w), described as the partial vapor pressure of water in a substance divided by the standard state partial vapor pressure of water. The water tolerance of microorganisms differs but most of them are unable to survive in an environment with water activity less than 0.90 (Brown, 1990). Hypothetically, in compacted bentonite saturated with just water, the water activity equals 1. However, the osmotic potential resulting from pore water salinity

and the suction potential exerted by the unsaturated soil matrix will decrease the water activity (Stroes-Gascoyne et al., 2007). Reducing the water activity is a potential approach in limiting microorganisms' activity in deep geological repositories, all the parameters affecting the development of microorganisms can be represented by the water activity (Stroes-Gascoyne et al., 2010). In the case of deep geological repositories, the literature has suggested that the water activity must be lower than 0.96 to render microorganisms inactive and unable them to grow through normal metabolic activity. (Stroes-Gascoyne and West, 1997; King, 1996; Stroes-Gascoyne et al., 2010; Stone et al., 2016). Stroes-Gascoyne et al. (1996a) showed that in water contents below 15%; culturable bacteria could not survive on culture media (Stroes-Gascoyne et al., 2010).

2.5.2 Temperature

In a deep geological repository, due to the radioactive waste decay, it might experience elevated temperatures around 100-degree centigrade (Tabiatnejad et al., 2016). Temperatures greater than 100°C are used to sterilize surfaces. If the waste bundles are exposed to such temperatures the only explanation for survival of microorganisms is inoculation after the temperature drop (King, 2009). Bentonite clay based engineered barriers partially dry out and shrink away from the waste bundles at such temperatures. Despite these conditions, some microorganisms may survive as spores (Stroes-Gascoyne and West, 1997). Eventually, the temperature drops, and the ground water may infiltrate from the host rock locations into the repository system (Siddiqua et al., 2014; Stroes-Gascoyne et al., 2010; King, 2009). This typically creates preferable environment for the growth of microorganisms and may also support the microbial induced corrosion. Several studies have been conducted regarding the effect of temperature on the culturability of the microorganisms (Stoecker et al., 1986; Stroes-Gascoyne et al., 2007; Stroes-Gascoyne et al., 2010; King, 2009; Pedersen, 2000). A statistical evaluation by King and Stroes-Gascoyne (1995) demonstrated that

the factor limiting the culturability of the microorganisms in the barrier materials is the water content not the temperature. This emphasizes the significance of water activity and its relationship with temperature (Stroes-Gascoyne and West, 1997).

2.5.3 Radiation

Nuclear waste bundles would emanate radiation alongside heat, creating an inhospitable situation for some microorganisms. Thus, at the time of emplacement of nuclear waste bundles the effects of radiation would be present almost instantly. Depending on the total radiation dose, most of the microorganisms are inactivated or eradicated in the immediate areas near the waste bundles. This could mean that microbial induced corrosion is not a concern for a brief time after waste bundle placement. D_{10} value is used to express the decrease in the number of culturable microorganisms as a function of increasing radiation, which is the radiation dose needed to eradicate 90% of culturable microorganisms' population (Mayfield and Barker, 1982). It was reported that 1 kGy (0.1 MRad) is sufficient to suppress the microorganisms' activity at the waste bundles' surface (Stroes-Gascoyne et al., 1994). The existence of radiation-tolerant microorganisms in the repository environment has been reported (King, 2009). These microorganisms developed an extensive DNA repair system through an evolutionary process (e.g. desiccation) which enable them to repair DNA damage from ionizing radiation (Mattimore and Battista, 1996). Based on the literature, it may not be possible to conclude that the radiation will wipe microorganisms out, but it severely reduces the microorganisms' activity near the waste bundles' surface (Stroes-Gascoyne et al., 1994). At some distance, away from the waste bundles' surface, microorganisms could be able to survive the radiation. The diffusion of corrosive metabolic products from these microorganisms might lead to microbial induced corrosion (King and Stroes-Gascoyne, 1995).

2.5.4 Mass transfer

One of the main reasons in covering the waste bundles with compacted bentonite is to limit mass transportation in the case of waste bundle failure. Hydraulic conductivity of the compacted bentonite clay is low; thus, the mass transfer through it is by diffusion only (Lovley and Klug, 1986; Choi and Oscarson, 1996). Mass transport processes could play several roles in microbial induced corrosion of the waste bundles. As mentioned before, it is possible that the combination of the several factors like elevated temperature, low water activity and radiation deplete the microorganisms' population near the waste bundles surface. If this happens, then microorganisms' activity near the waste bundles is only possible if this zone can be repopulated once those conditions have been improved. However, literature have shown that this may not be possible since the typical pore size (approximately, 0.02 μm) is smaller than microorganisms (Stroes-Gascoyne et al., 1996b; Wan et al., 1995; Doig et al., 1995). Furthermore, low hydraulic conductivity of compacted bentonite will further restrict the supply of nutrients to regions with culturable microorganisms (King, 2009). The low hydraulic conductivity of bentonite based clay barriers limits the transport of corrosive microbial metabolites and microorganisms from the host rock through the barriers by creating a diffusion-dominated environment (Stroes-Gascoyne et al., 1997; Hallbeck and Pedersen, 2012; Pedersen, 2010; Stone et al., 2016).

2.5.5 Bentonite dry density/swelling pressure

Swelling pressure above 2MPa is desired in a deep geological repository to suppress the activity of microorganisms which keeps the water activity below 0.96 (Stroes-Gascoyne et al., 2010). In practice, this swelling pressure can be achieved for a uniform dry density more than 1.6 g/cm^3 for highly compacted bentonite (Stroes-Gascoyne et al., 2007). Specification of a threshold for compacted bentonite dry density (1.6 g/cm^3) brings the advantage of a minimum barrier material production requirement. Barrier materials are typically designed with a minimum dry density of

1.6 g/cm³, which is intended to swell at the re-saturation period. During the ground water infiltration, it is possible that some regions develop low dry density, which may favor the microorganisms' activity. Some of the reasons for development of this low dry density regions includes but is not limited to, bentonite swelling in the placement gaps, unbalanced swelling pressure at the interfaces of different barrier materials and high infiltration water pressure able to push the barrier materials and create gaps in the repository. If the reduction in dry density is sufficiently below 1.6 g/cm³, it may favor the microbial induced corrosion (Stroes-Gascoyne et al., 2010).

2.5.6 Salinity

Saline pore water introduces osmotic potential which will affect the water activity and as a result the microorganisms' activity in the deep geological repository (Stroes-Gascoyne et al., 2007). According to literature, pore water salinity higher than 100g/L is sufficient to prevent the growth of indigenous microorganisms (Stroes-Gascoyne et al., 2007; Stroes-Gascoyne et al., 2010; NWMO, 2007; Jalique et al., 2016). As previously discussed, there are places in the repository where the intended uniform dry density of 1.6 g/cm³ may be reduced. High salinity can suppress microorganisms' activity in these areas. In a study conducted by NWMO (2010), the effect of CaCl₂ solution on the microorganisms' activity is compared with that of NaCl. At the same concentrations, water activity of samples infused with CaCl₂ is higher than those with NaCl. The reason is CaCl₂'s higher ionic activity which could yield a more compressed diffuse double layer. This will exclude the previously bound water molecules and result in more free water and a higher water activity for the CaCl₂ infused samples (NWMO, 2008).

Concisely, to limit the water activity and prevent microbial induced corrosion, several parameters like highly compacted bentonite's swelling pressure resulted from its dry density and also natural salinity of groundwater, are relied upon (Stroes-Gascoyne et al., 2010; Masurat et al., 2010).

Among these parameters affecting the microorganisms' activity in a deep geological repository, salinity was chosen for further study. Earlier research studies investigated engineered barrier hydraulic, mechanical and microstructural properties in the Canadian context, under the influence of pore fluid salinity (Siddiqua et al., 2011a, 2014; Sarkar and Siddiqua 2016a, 2016b; Tabiatnejad et al., 2016). To further enhance the knowledge on barrier materials, this research is focused on determining highly compacted bentonite's salinity by means of electrical resistivity. Determination of the in-place salinity will be of significant help in estimating the microorganisms' activity and the related corrosion concerns.

Chapter 3: Material and methods

3.1 Sample preparation

Canadian Deep geological repository design includes blocks of highly compacted bentonite with a dry density of 1.61 g/cm^3 to hold the cylinders of waste bundles in place. The dimensions of these blocks are 2.8 m in length and have a height/width of 1 m (NWMO, 2016). Highly compacted bentonite samples in this study are prepared from two bentonite types: MX-80 and Wyoming (National standard) bentonite. MX-80 and Wyoming bentonite are both sodium bentonites. MX-80 bentonite has an average particle size of 30 to 200 μm . The liquid limit of the MX-80 bentonite is 350-570% and its plastic limit is 70. Wyoming bentonite is a natural 200 μm bentonite with a liquid limit of 625% and plastic limit of 45 (Villar, 2005; Blatz et al., 2007).



Figure 3.1 National standard and MX-80 Bentonite

Ground water at the proposed geological location of the nuclear waste repositories is predominantly saline; containing mostly Sodium, Calcium and chloride ions (Siddiqua et al., 2011b, 2014). Therefore, in this study, calcium and sodium chlorides were selected to prepare

synthetic solutions in the laboratory. Concentrations of CaCl_2 and NaCl which were considered in the experimental program are 50, 100 and 250 g/L. The pore fluid is saline which adds a new component to the soil system, i.e., solid, gas, solvent and solute.



Figure 3.2 Prepared NaCl and CaCl_2 solution

All specimens were prepared using the process proposed by Siddiqua et al. (2011a). The process starts by placing bentonite in a mixing bowl, then it can be oven dried at 105°C for at least 24 hours. Afterwards it can be removed from the oven, sealed in plastic bags, and allowed to come to thermal equilibrium. A measured amount of CaCl_2 / NaCl solution or distilled water is then added to the sample and mixed to reach the targeted moisture content. Following mixing, the soil was sealed in plastic bags and refrigerated at 4°C for at least 48 hours to reach complete clay hydration and homogeneous distribution of moisture throughout the mixture. The specimens were then compacted in two 20-mm lifts to a target diameter and height of 50 and 40 mm, respectively. After completing the electrical resistivity test, samples were extruded using a hydraulic jack and a sample extruder, then the weight of the sample was measured to confirm the dry density of 1.61

g/cm^3 .

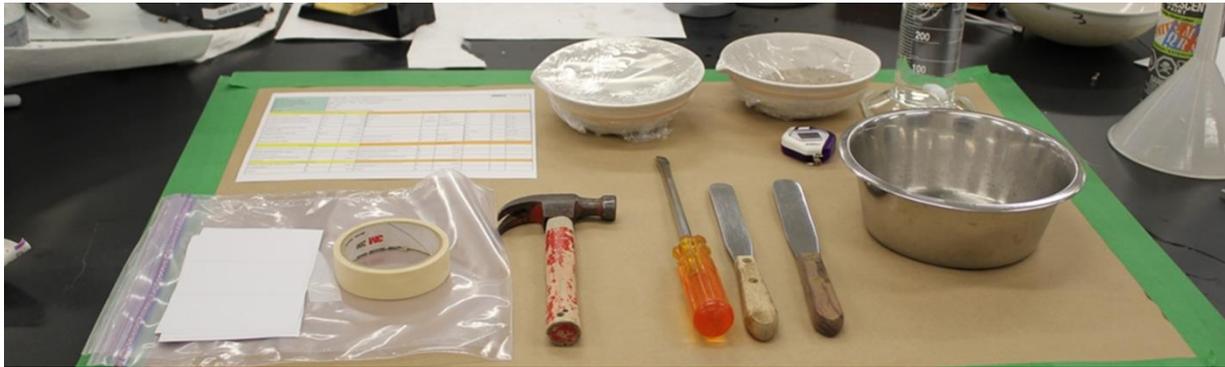


Figure 3.3 Mixing tools for preparing the mixtures



Figure 3.4 Highly compacted bentonite Specimen

3.2 Experimental Program

3.2.1 Electrical measurement method

The compaction mold, shown in Figure 3.1, used for measuring the electrical resistivity of the samples features a bottom-fixed copper electrode with a removable PVC cylinder covering the compacted bentonite sample. The purpose of using a PVC mold is to ensure electrical isolation during the electrical resistivity tests. A mobile top electrode is inserted at the top of the samples with enough force on it to ensure decent soil-electrode contact. An alternating current (AC) power source is used because the application of direct current (DC) can cause electro-kinetic phenomena which may disturb pore fluid chemistry, water content, and soil structure (Abu-Hassanein et al., 1996a; Arulanandan and Smith, 1973). The frequency of 60 Hz was chosen for this experiment after comparing the measured electrical resistivity of the samples with a range of frequencies between 10 to 5k HZ. A 60 HZ frequency was also chosen mainly because it is the most common frequency in AC supplies; thus, it is more practical than other frequencies to be used in field applications. Additionally, polarization will not affect the electrical properties of the soil samples at this frequency. (Abu-Hassanein et al., 1996a; Hamed et al., 1991; Rinaldi et al., 2002). To perform the electrical resistivity test, a range of voltages between 10 and 40 was used to ensure a consistency in the calculation of electrical resistivity. The test begins at 10 V and is increased in intervals of 5V, with current measurements taken at every interval. This procedure was repeated three times to further ensure consistency, and the average resistance was calculated from these readings. BK Precision 2880B multi-display multi-meter was used for measuring the voltage and current. To calibrate the readings, before each electrical test the electrical resistance of the whole electrical circuit without the soil sample was measured. Since the soil samples are placed in series with the electrical circuit, by subtracting the previously measured electrical resistance from the readings with the soil sample the data can be calibrated.

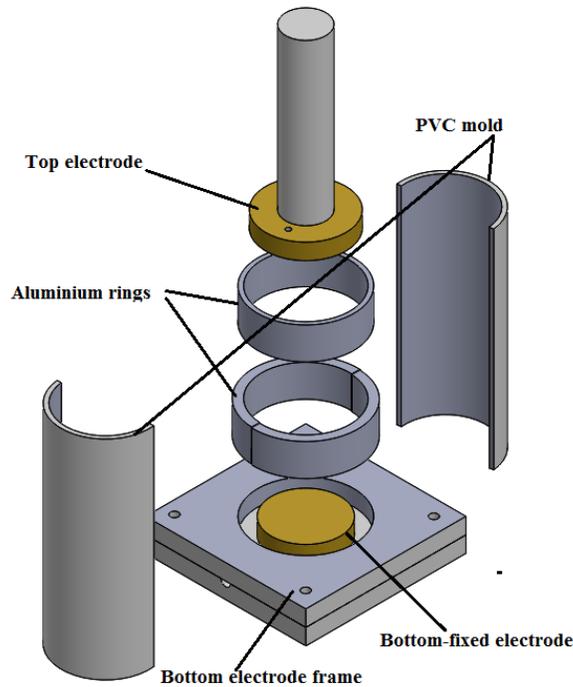


Fig 3.5 Compaction mold and electrical resistivity apparatus. Adopted from Rahimi and Siddiqua, (2017)

3.2.2 Thermal measurement method

Following the electrical resistivity tests, the bottom electrode was disconnected, and the samples were penetrated for thermal resistivity tests. KD2 Pro thermal properties analyzer manufactured by Decagon Devices was used to measure the thermal resistivity of the samples. KD2 pro incorporates the infinite line heat source theory (Carslaw and Jaeger, 1959). It measures the thermal resistivity of the soil samples by monitoring the dissipation of heat from the needle probe (Decagon Devices, 2006). The probe was calibrated prior to testing using glycerol provided by the manufacturer. Tabiatnejad et al. (2016) presented a testing protocol which is followed in this research.



Figure 3.6 Highly compacted bentonite's thermal resistivity measurement

3.2.3 Suction measurement method

Using the same batches of samples prepared for the electrical/thermal resistivity tests, additional compacted soil samples were made to perform suction measurements. A relative humidity sensor (Rotronics Hygroclip Relative Humidity sensors-model # HC2-S) was used to measure the total suction values. The sensor was calibrated using distilled water. Compacted samples were penetrated at the center to allow a suction tip to be placed on a penetrated sample. Figure 3.2 shows a sealed sampled and relative humidity sensor. From the relative humidity readings, the total suction was calculated at each degree of saturation, using Kelvin's equation (Fredlund and Rahardjo, 1993).

$$\psi = -\frac{RT}{M_w\left(\frac{1}{p_w}\right)} \cdot \ln(RH) \quad (3.1)$$

where ψ = Total suction in soil (kPa), R = gas constant (8.314 J/mol.K), T = temperature (K), M_w = molecular weight of water (18.016 kg/kmol), p_w = unit weight of water in kg/m^3 .

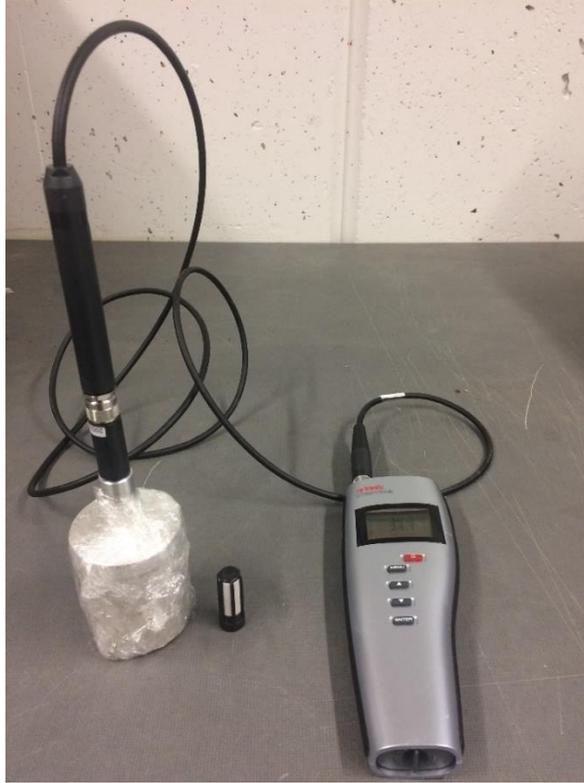


Fig 3.7 Relative humidity measurement device. Adopted from Rahimi and Siddiqua, (2017)

Chapter 4: Results and discussion

4.1 Developing correlation between thermal/electrical resistivity, total suction and degree of saturation for highly compacted bentonite

Both MX-80 and Wyoming bentonite samples were tested to observe any changes of electrical resistivity with the change in the degree of saturation and the relationship is presented in Figure 4.1. Generally, the electrical resistivity of both bentonites decreases exponentially as the degree of saturation increases, indicating that the electrolyte is the main source of current transfer in the compacted bentonite sample. By comparing the electrical resistivity of two bentonites in the same degree of saturation, MX-80 bentonite samples appear to have more resistance to electrical flow than Wyoming bentonite samples.

This trend may be attributable to the role of available exchangeable cations. It is shown by Kaufhold et al. (2015), that the existence of exchangeable calcium generally increases the electrical resistivity of the bentonite. MX-80 typically has a higher exchangeable calcium content than Wyoming bentonite which will lead to a higher amount of electrical resistivity.

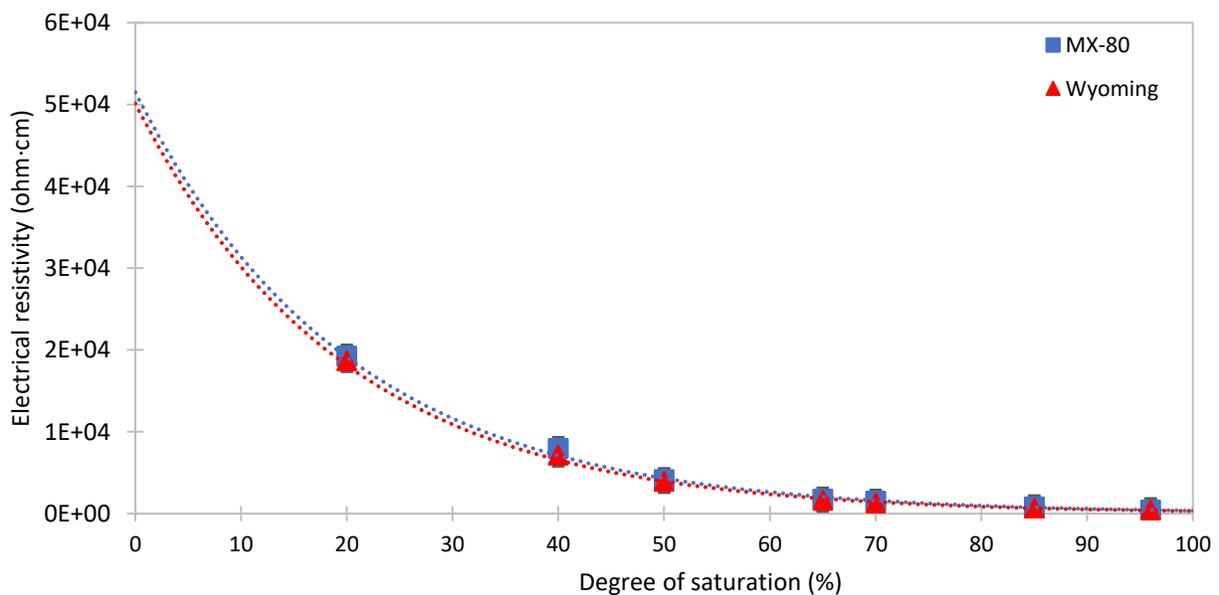


Fig 4.1 Relation between electrical resistivity of compacted Mx-80 and Wyoming bentonite samples with respect to degree of saturation. Adopted from Rahimi and Siddiqua, (2017)

Additionally, the values of thermal resistivity for each degree of saturation of the MX-80 and Wyoming bentonites were investigated. The thermal resistivity was plotted versus the degree saturation as shown in Figure 4.2.

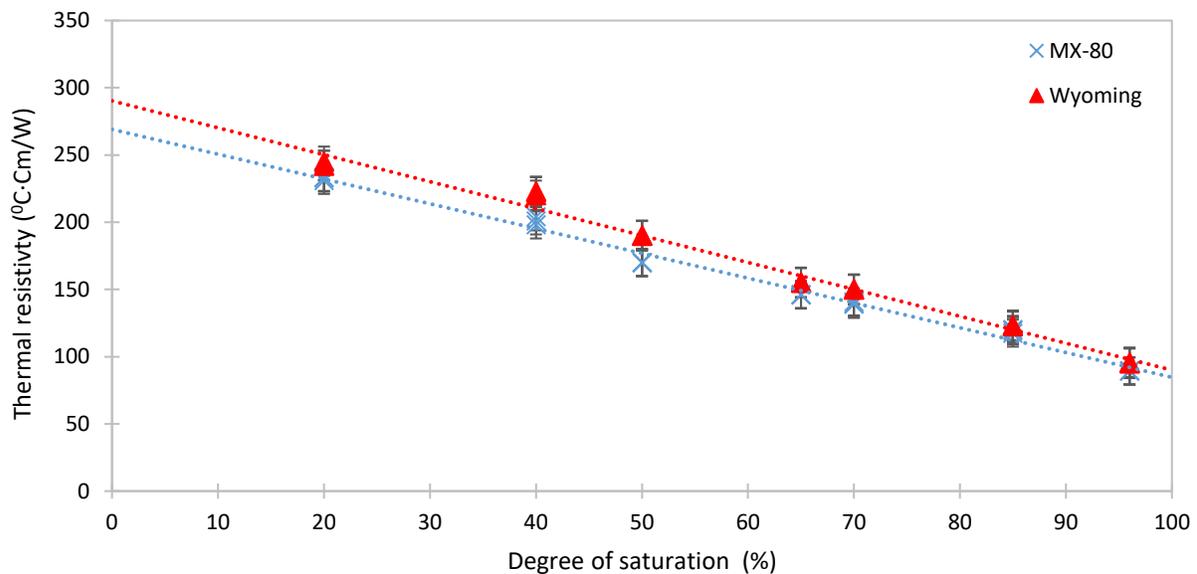


Fig 4.2 Relation between thermal resistivity of compacted Mx-80 and Wyoming bentonite samples with respect to degree of saturation. Adopted from Rahimi and Siddiqua, (2017)

It is observed that the thermal resistivity of both bentonites decreases with increasing the degree of saturation in a linear trend which emphasizes on the role of electrolyte in heat transfer. For the sake of convenience of analyzing trends depicted in Figures 4.1 and 4.2, natural logarithm of electrical resistivity was plotted against the degree of saturation (shown in Figure 4.3).

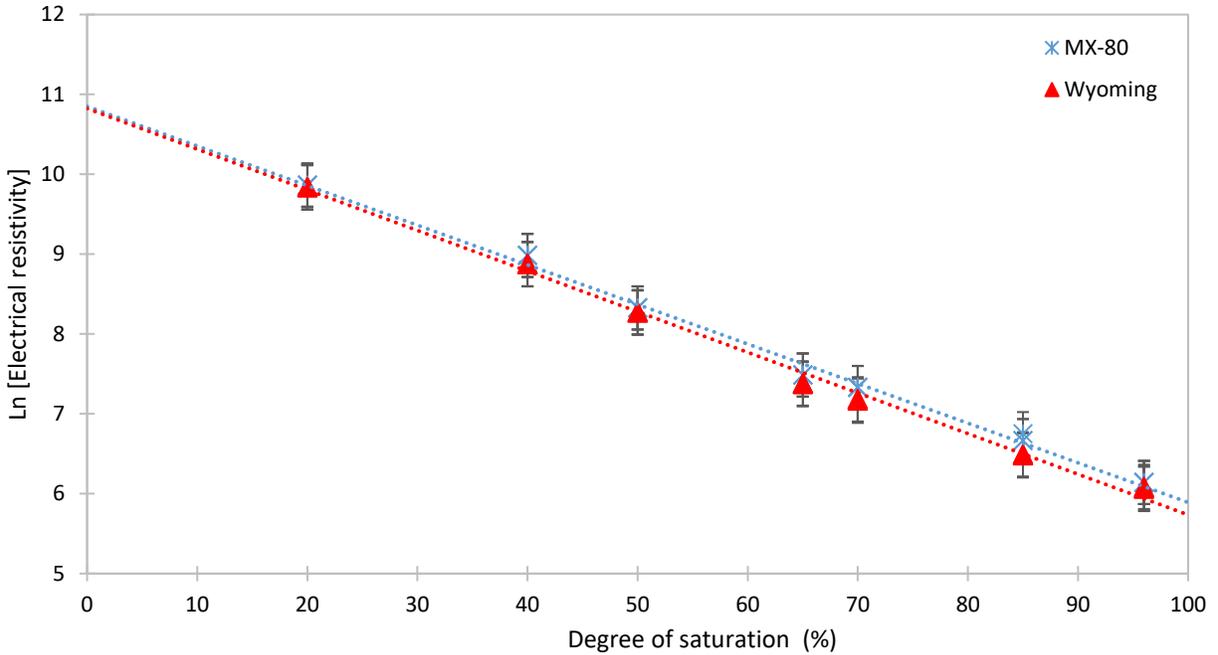


Fig 4.3 Variation of the natural logarithm of electrical resistivity with degree of saturation for compacted Mx-80 and Wyoming bentonite samples. Adopted from Rahimi and Siddiqua, (2017)

For any given degree of saturation, the relationship between thermal resistivity and the natural logarithm of the electrical resistivity can be represented by the following equation:

$$\ln(E_R) = M_T T_R \quad (4.1)$$

where E_R is the soil electrical resistivity (ohm·cm), T_R is the soil thermal resistivity ($^{\circ}\text{C}\cdot\text{cm}/\text{W}$), and M_T is the thermal multiplier which can be used to relate electrical resistivity and thermal resistivity. Sreedeeep et al. (2005) suggested that M_T depends on both degree of saturation and the sand fraction of the soil sample. Since this current experimental project is based on clays, therefore, M_T in this study was developed based on degree of saturation only. Average M_T values for each degree of saturation are shown in Figures 4.4 and 4.5.

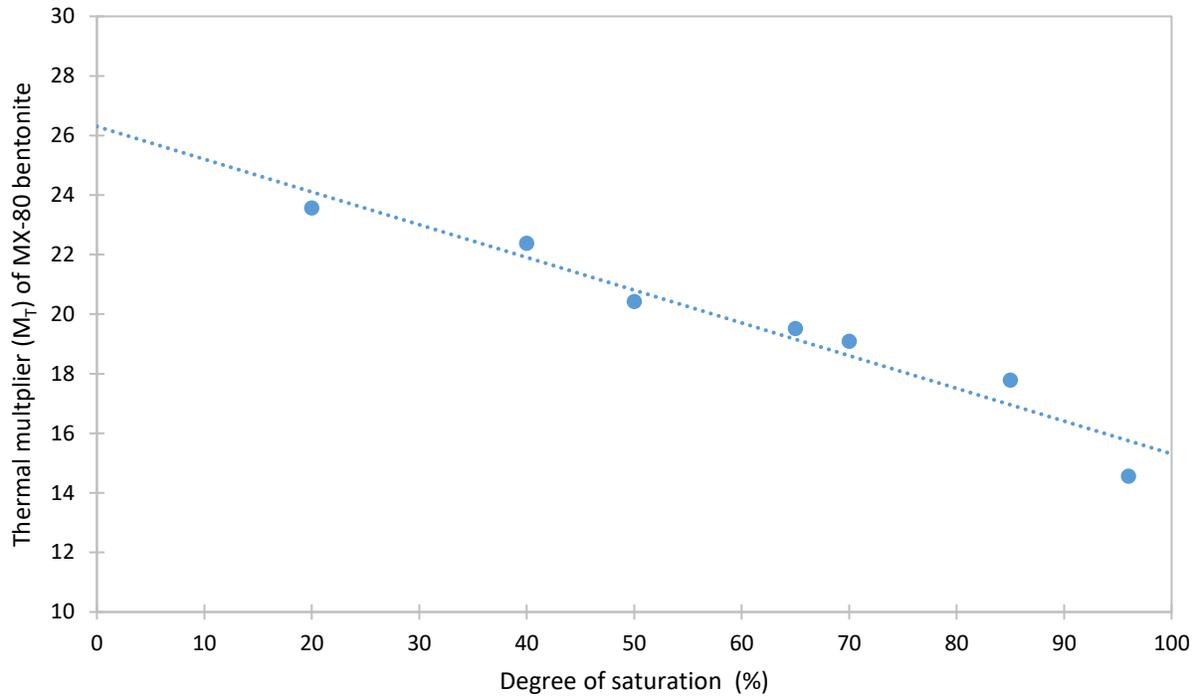


Fig 4.4 Variation of thermal multiplier (M_T) with degree of saturation for compacted Mx-80 samples. Adopted from Rahimi and Siddiqua, (2017)

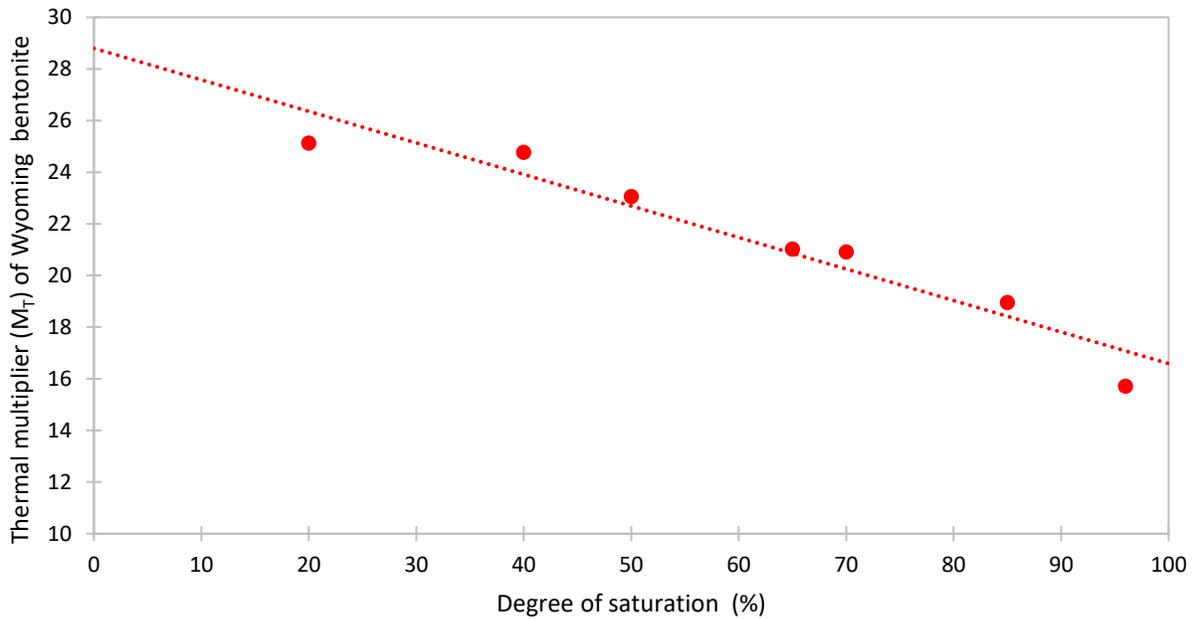


Fig 4.5 Variation of thermal multiplier (M_T) with degree of saturation for compacted Wyoming bentonite samples. Adopted from Rahimi and Siddiqua, (2017)

As observed in Figures 4.4 and 4.5, the values of M_T depend on the degree of saturation. Equation 4.2 shows the relationship between the thermal multiplier and degree of saturation.

$$M_T = XS_r + Y \quad (4.2)$$

where X is -0.1099 and -0.1221 for Mx-80 and Wyoming bentonite respectively, and Y is 26.301 and 28.798 for Mx-80 and Wyoming bentonite respectively. Comparing the MX-80 and Wyoming bentonite thermal multipliers shows that the Wyoming bentonite's thermal multiplier is more sensitive to degree of saturation than that of the Mx-80.

Total suction is one of the fundamental properties when studying an engineered barrier system and having an estimation of this property will further clarify the performance of the deep geological repository. Thus, investigating its relationship with electrical resistivity will be of significant help when studying the behavior of the deep geological repository. The same procedure can be used to develop a relation between soil electrical resistivity and suction. Figure 4.6 shows the changes in suction with various degree of saturation for both bentonite types.

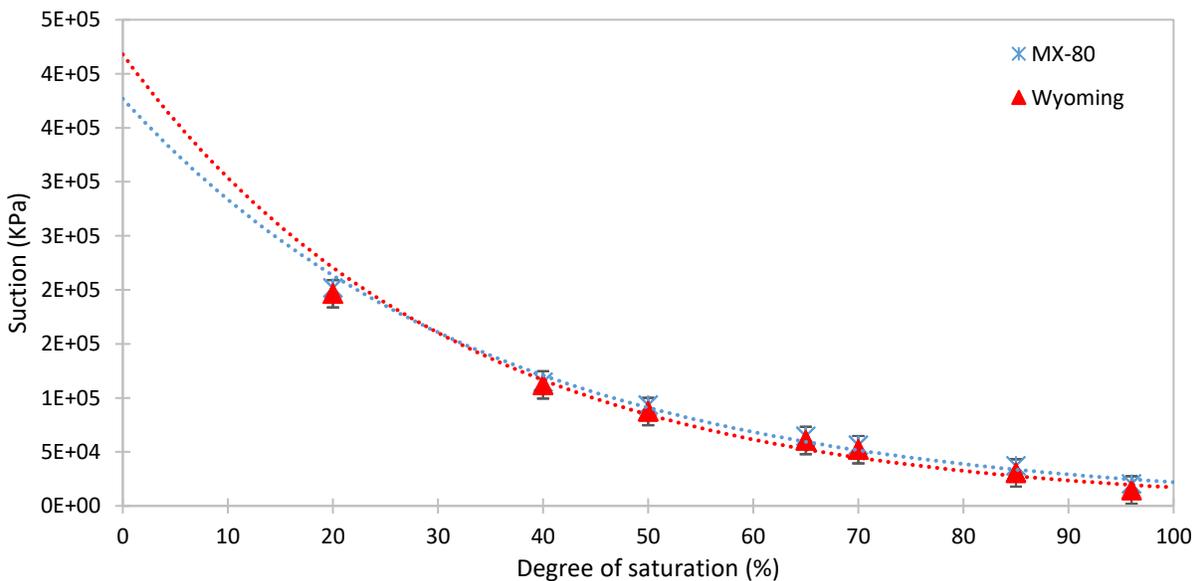


Fig 4.6 Variation of total suction for compacted Mx-80 and Wyoming bentonite samples with degree of saturation. Adopted from Rahimi and Siddiqua, (2017)

Again, for the sake of convenience of analyzing the trends depicted in Figures 4.2 and 4.6, natural logarithm of suction is plotted against degree of saturation and compared with natural logarithm of electrical resistivity. (Figures 4.3 and 4.7).

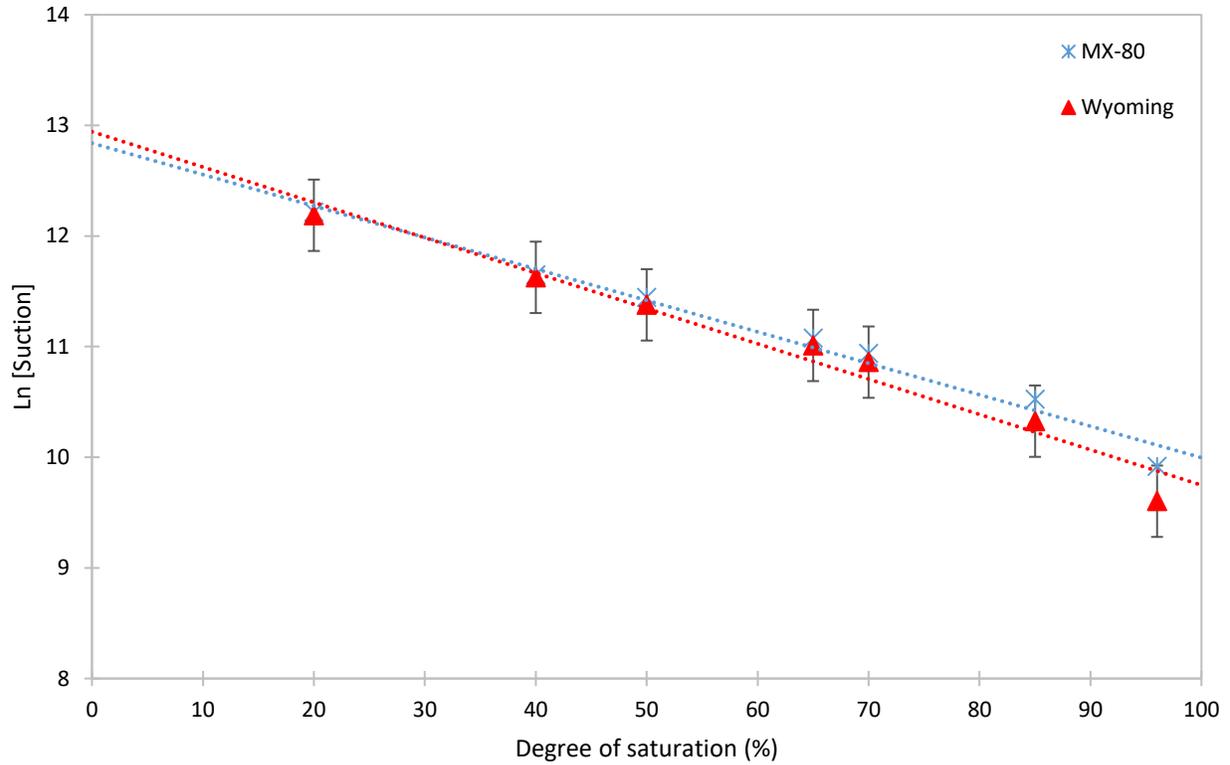


Fig 4.7 Variation of total suction natural logarithm with degree of saturation for compacted Mx-80 and Wyoming bentonite samples. Adopted from Rahimi and Siddiqua, (2017)

A relationship between the trends depicted in the Figures 4.3 and 4.7 for the two types of bentonite can be expressed in the following equation:

$$\text{Ln } \psi = M_s \cdot \text{Ln } E_R \quad (4.3)$$

where E_R is the electrical resistivity, ψ is total suction and M_s is the multiplier which relates the suction and electrical resistivity. Figures 4.8 and 4.9 show the trends of M_s with different degrees of saturation.

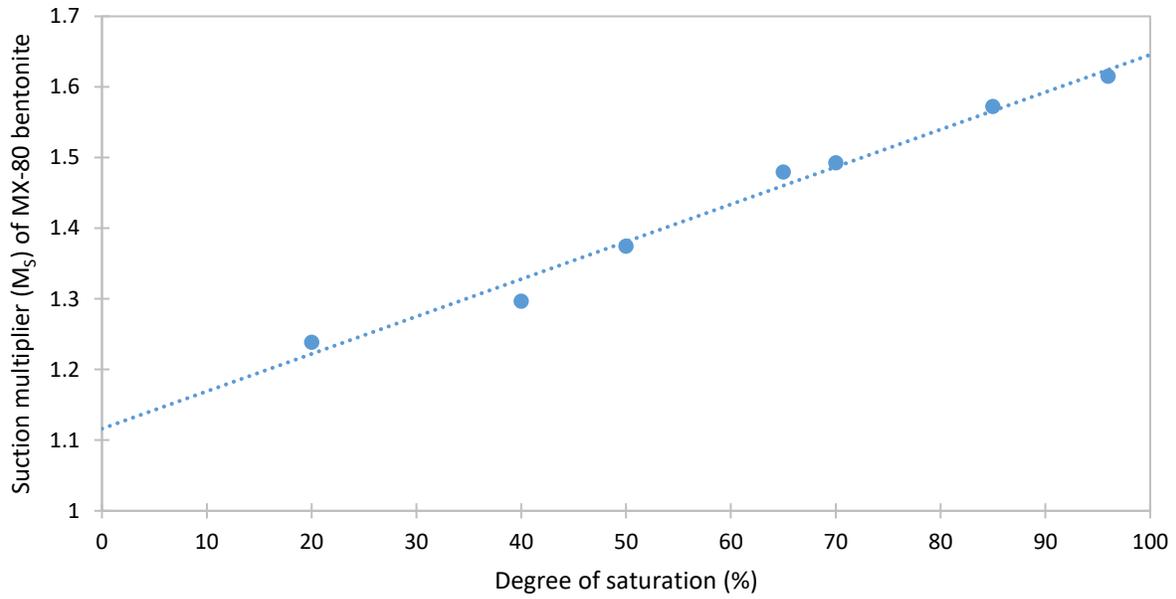


Fig 4.8 Variation in Suction multiplier (M_s) versus degree of saturation for compacted MX-80 samples. Adopted from Rahimi and Siddiqua, (2017)

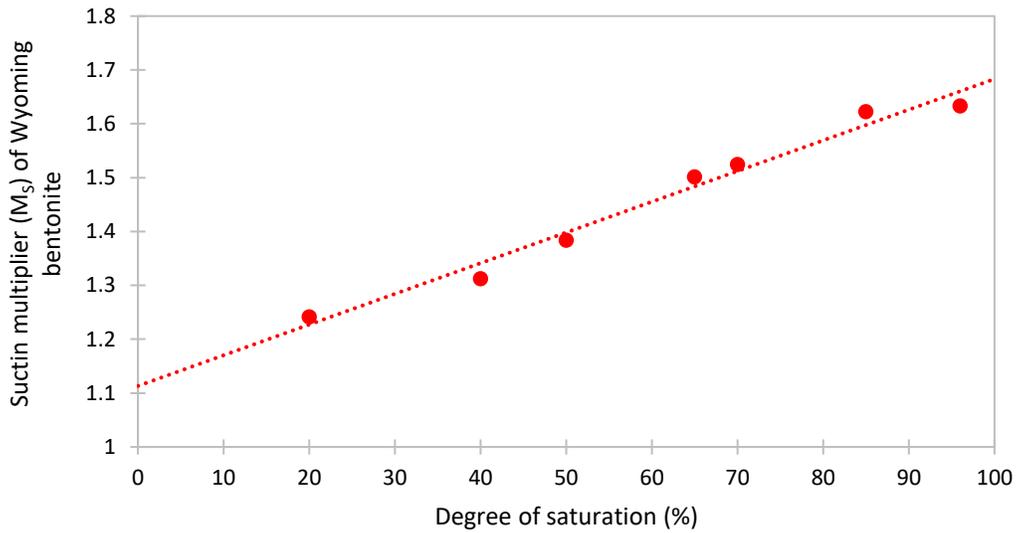


Fig 4.9 variation of Suction multiplier (M_s) with degree of saturation for compacted Wyoming bentonite samples. Adopted from Rahimi and Siddiqua, (2017)

Finally, Equation 4.4 shows the dependence of the suction multiplier on degree of saturation.

$$M_s = X^1 \cdot Sr + Y^1 \tag{4.4}$$

where X^1 is 0.0053 and 0.0057 for Mx-80 and Wyoming bentonite respectively. Y^1 is 1.1162 and 1.1133 for both Mx-80 and Wyoming bentonite respectively.

4.2 Establishing a relationship between electrical resistivity, degree of saturation, pore fluid salinity and microbial activity for highly compacted bentonite.

Figures 4.10 to 4.13 show the electrical resistivity measurements of compacted bentonite samples at different degrees of saturation and salt concentrations.

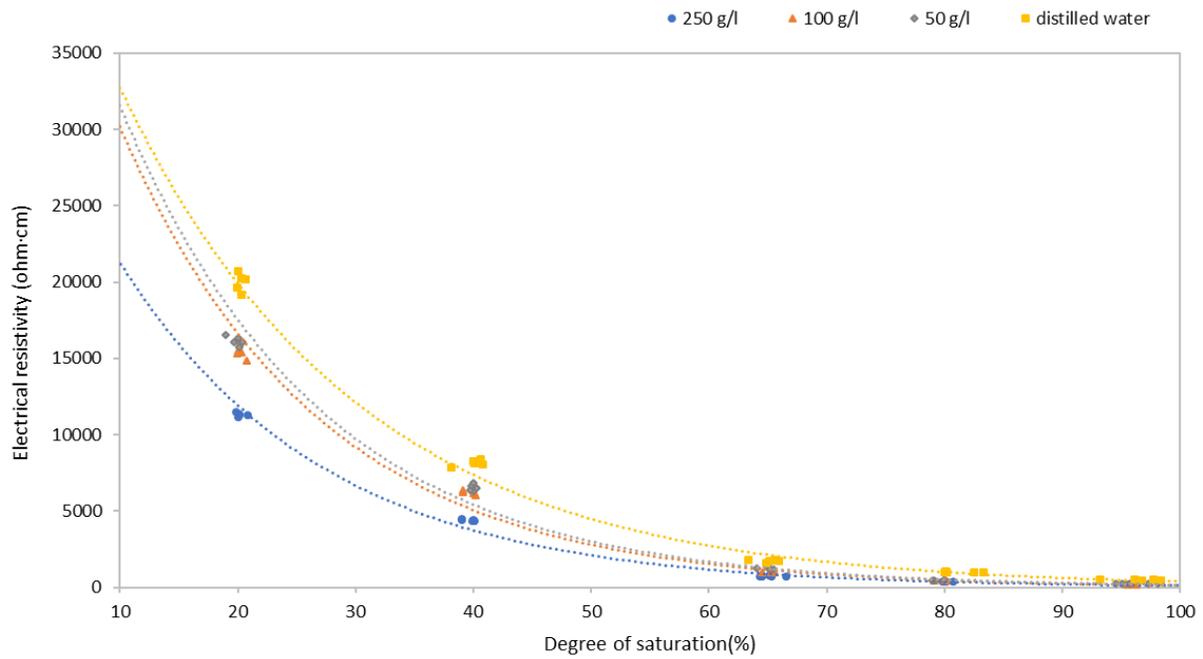


Fig 4.10 Relationship between electrical resistivity of compacted Mx-80 samples with respect to degree of saturation at different CaCl_2 concentrations.

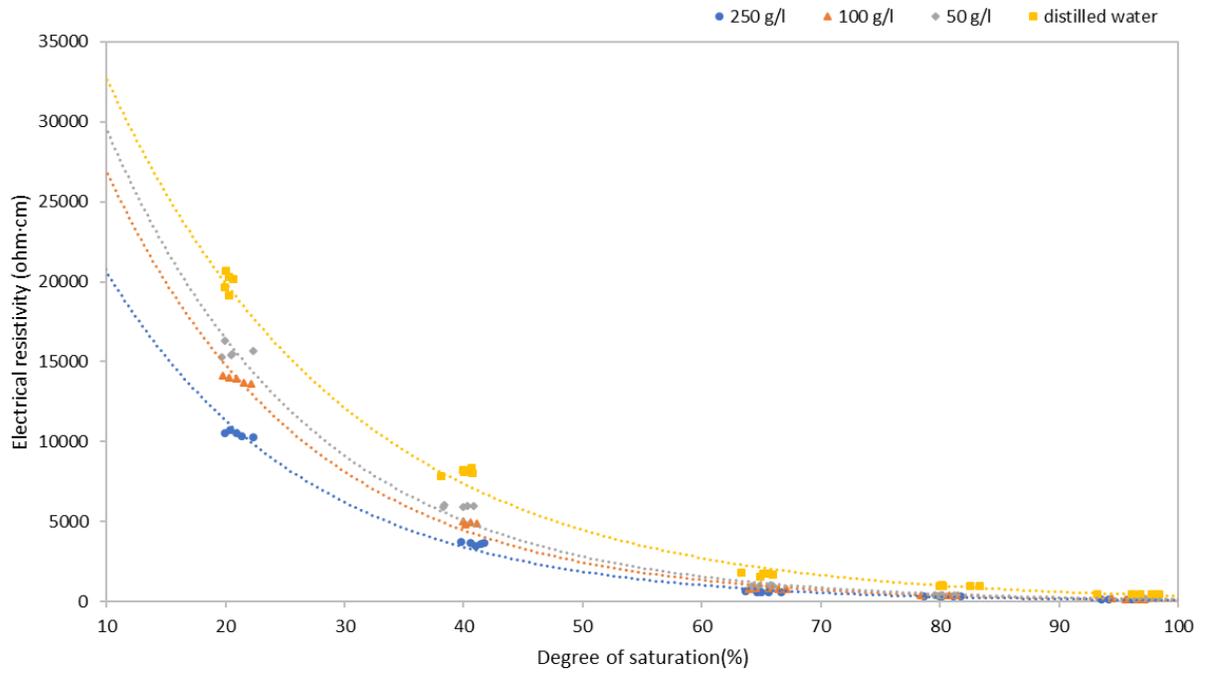


Fig 4.11 Relationship between electrical resistivity of compacted Mx-80 samples with respect to degree of saturation at different NaCl concentrations.

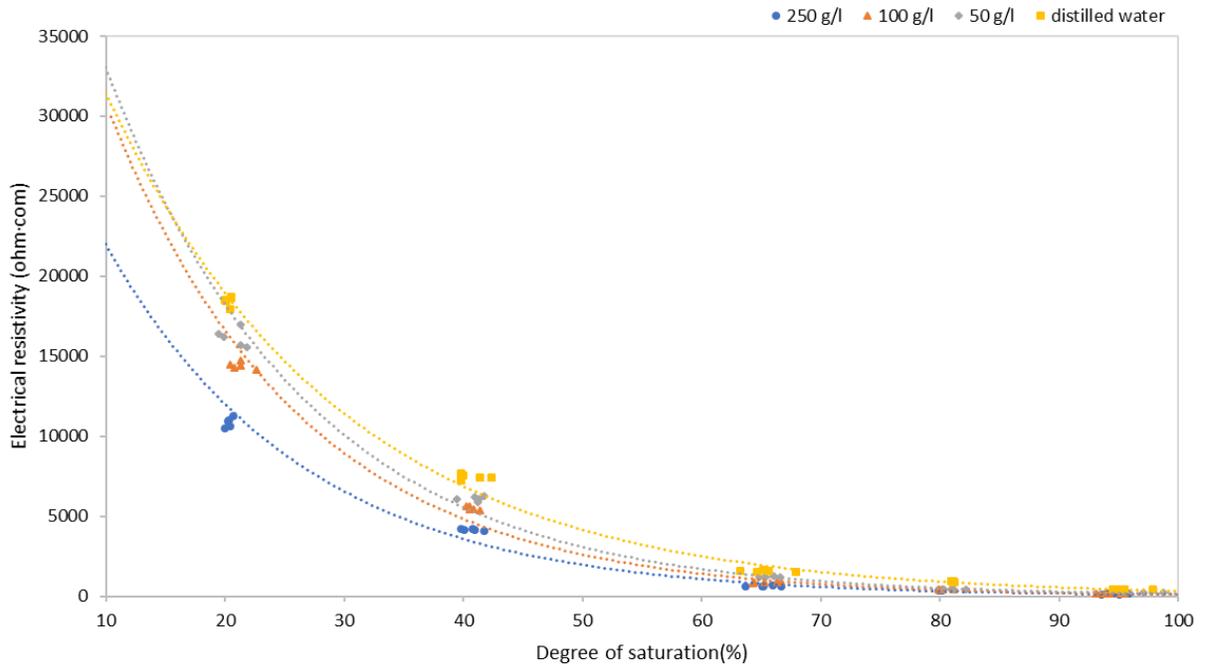


Fig 4.12 Relationship between electrical resistivity of compacted Wyoming (National standard) samples with respect to degree of saturation at different CaCl₂ concentrations.

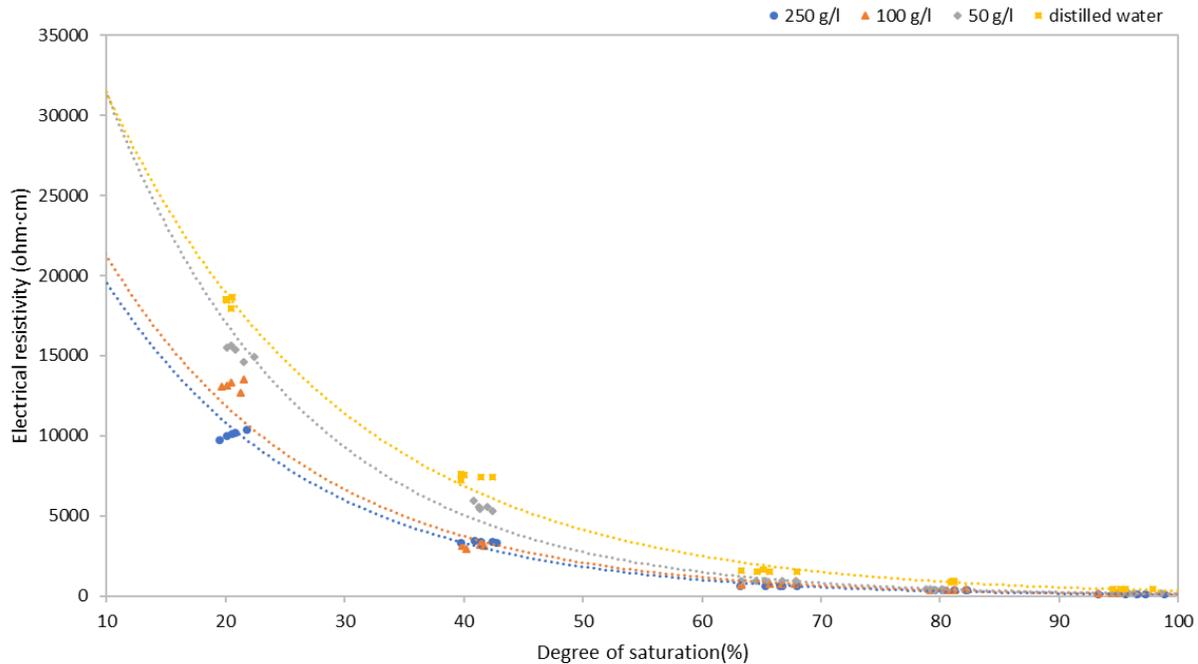


Fig 4.13 Relationship between electrical resistivity of compacted Wyoming (National standard) samples with respect to degree of saturation at different NaCl concentrations.

Based on the literature, 100g/L is the threshold to suppress the microorganisms' activity of bentonite samples having 1.61 g/cm^3 and 95% of dry density and degree of saturation, respectively (Stroes-Gascoyne et al., 2007; Stroes-Gascoyne et al., 2010). At 100g/L microorganism's activity is smaller than its background level which is $2.0 \times 10^2 \text{ CFU/g}$. (Stroes-Gascoyne et al., 2007; Stroes-Gascoyne et al., 2010; NWMO, 2007; Jalique et al., 2016). It is also shown by Stroes-Gascoyne et al. (1996a) that at water contents below 15%; culturable microorganisms can not survive.

In order to estimate the microorganisms' activity with electrical resistivity measurements, Figures 4.10 to 4.13 are replotted to indicate the situations with potential microorganisms' activity ($>2.0 \times 10^2 \text{ CFU/g}$) and zero microorganisms' activity. Yellow and purple colour are used to show potential microorganisms' activity ($>2.0 \times 10^2 \text{ CFU/g}$) and zero microorganisms' activity, respectively.

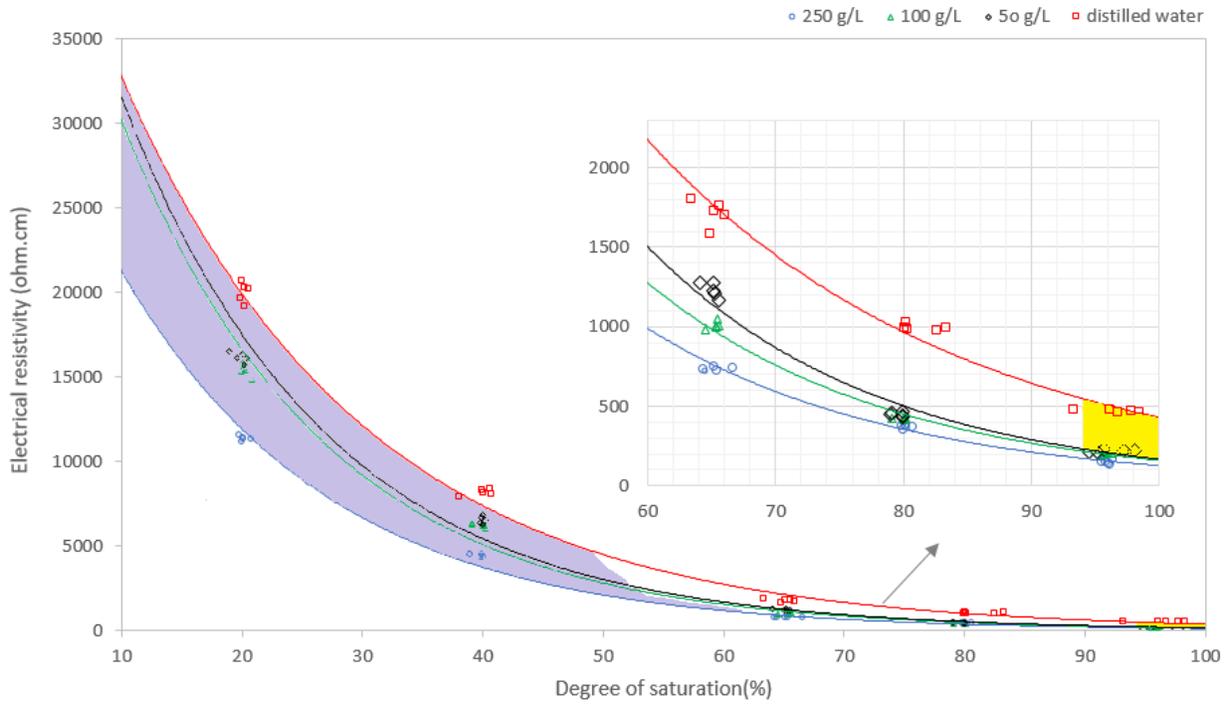


Fig 4.14 Relationship between electrical resistivity and microorganisms' activity of compacted Mx-80 samples at different CaCl_2 concentrations.

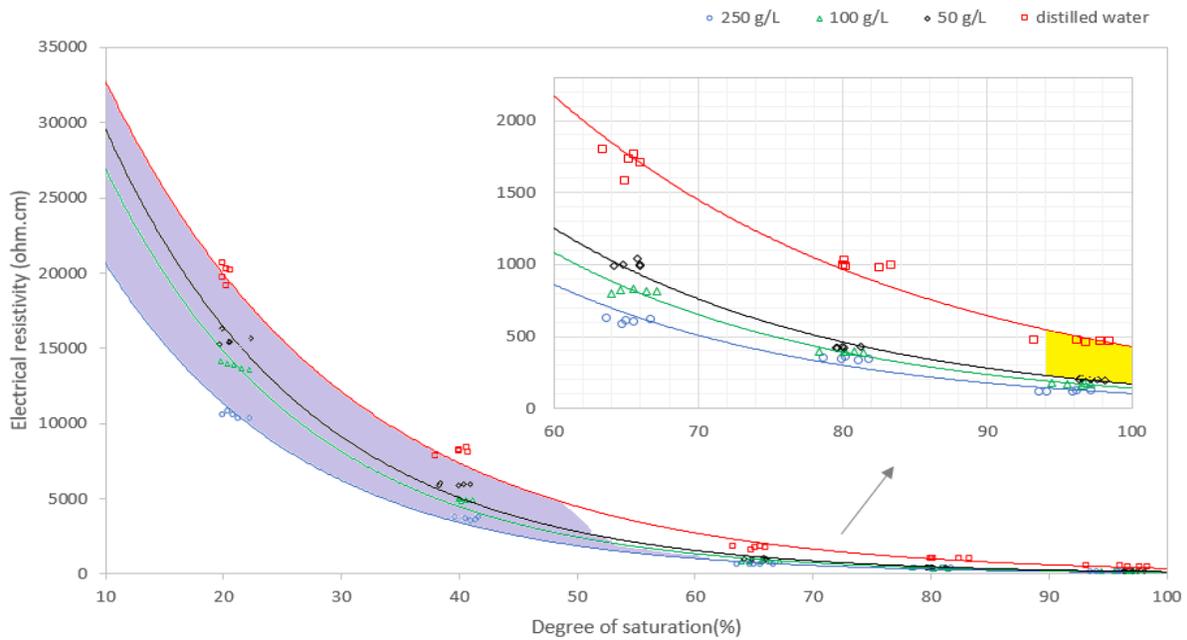


Fig 4.15 - Relationship between electrical resistivity and microorganisms' activity of compacted Mx-80 samples at different NaCl concentrations.

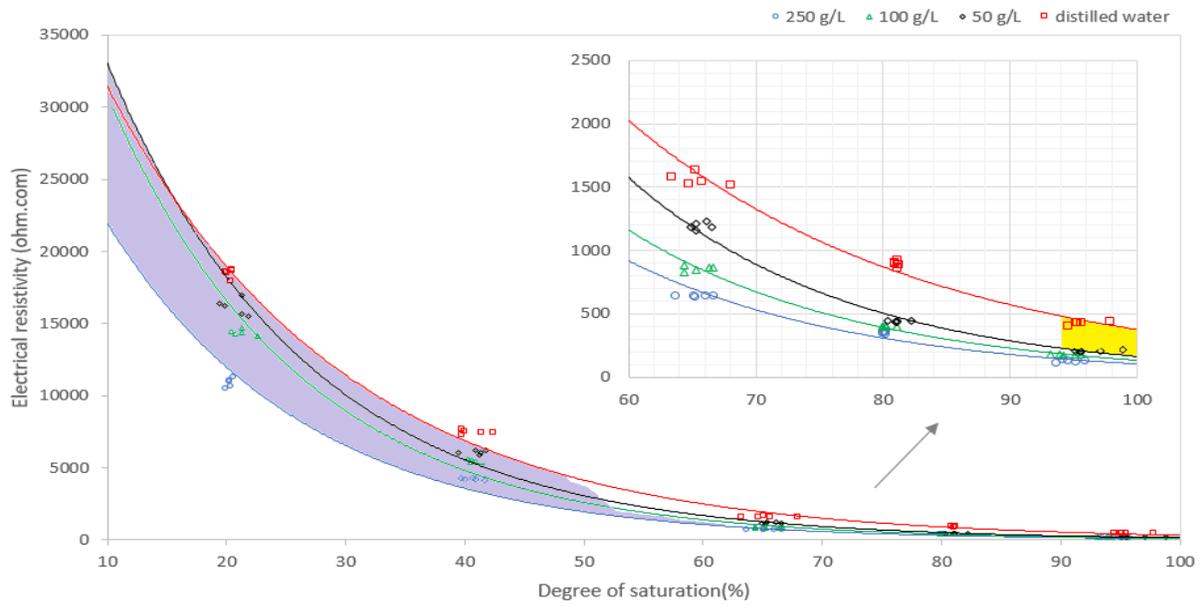


Fig 4.16 Relationship between electrical resistivity and microorganisms' activity of compacted Wyoming (National standard) samples at different CaCl₂ concentrations.

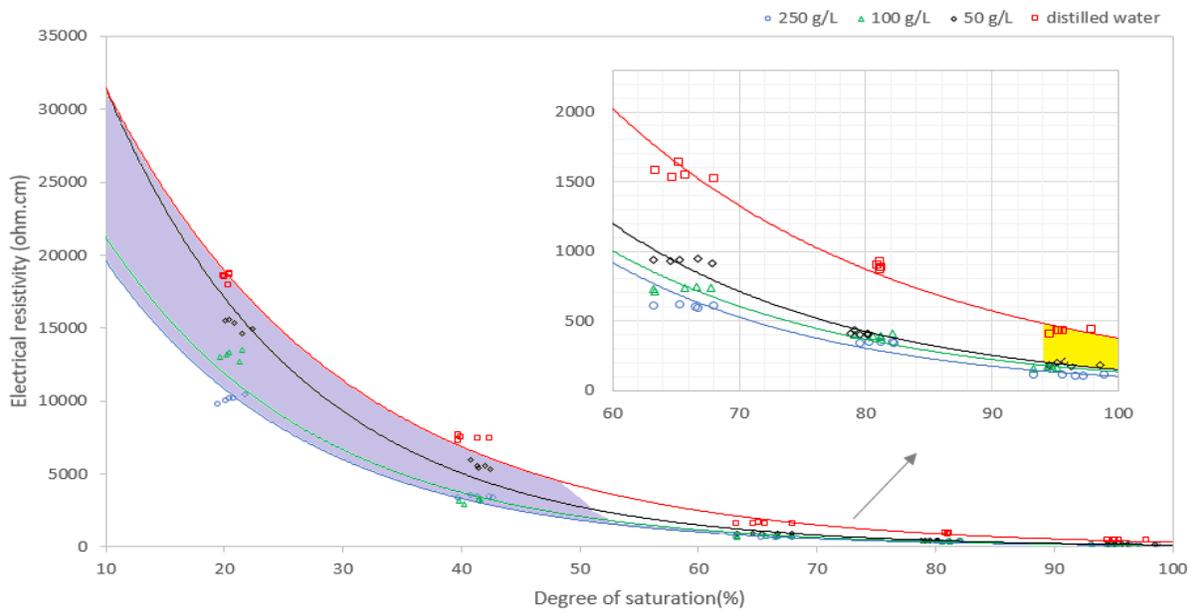


Fig 4.17 Relationship between electrical resistivity and microorganisms' activity of compacted Wyoming (National standard) samples at different NaCl concentrations.

Rahimi and Siddiqua (2017) showed that the in-place degree of saturation of both MX-80 and Wyoming (National standard) bentonite can be estimated with electrical and thermal resistivity measurements. Following the same procedure, once the in-place saturation is estimated, by using the relationships illustrated on Figures 4.14 to 4.17 the microorganisms' activity near the waste bundles can be estimated.

Chapter 5: Conclusions and Future Work Recommendations

5.1 Summary

The use of electrical resistivity measurements as a monitoring technique is a very valuable system for soil characterization. When compared with the classical soil monitoring techniques, measuring the electrical resistivity is non-destructive and provides continuous measurements over a broad range of scales. One of the key elements which attracts researchers to this area is the relation between soil resistivity and other geotechnical properties. Inspired by the previous works in this area, this thesis investigates possible relationships between highly compacted bentonite's electrical resistivity and other properties such as, thermal resistivity, total suction, saturation and salt concentration.

As part of a monitoring option to evaluate the deep geological repository's performance, it is important to know the in-place degree of saturation of barriers at a regular interval. Also, it is important to estimate the microorganisms' activity leading to corrosion of the waste bundles. The major findings can be outlined as follows:

- The electrolyte is the main source of heat and current transfer in the soils that's why soil electrical and thermal properties are related to each other. Highly compacted bentonite is not an exception. It is shown in this thesis that there is a generalized relation between these two resistivities and the degree of saturation (equation 4.1 and 4.2) for highly compacted Wyoming and MX-80 bentonite
- A relationship between total suction and electrical resistivity values is developed to estimate degree of saturation of highly compacted bentonite. This relation can be used in monitoring

in-situ degree of saturation of compacted bentonite based barriers at the deep geological repository environment.

- High salinity is a suppressing element regarding the microorganisms' activity at the deep geological repository. In this thesis, it is shown that the salinity of compacted bentonite can be estimated from its electrical resistivity. Which further enhances the suitability of electrical resistivity as a monitoring option for deep geological repositories.

5.2 Contributions to knowledge

- The need to monitor the saturation of the DGR environment has been a highly debated topic in the concept of nuclear waste disposal; since it takes time and money consuming surveys to estimate the saturation of the repository. In this study, a generalized relationship to estimate degree of saturation of highly compacted bentonite using electrical and thermal resistivity has been developed. Which is more efficient in both time and financial aspects.
- A new monitoring technique, using HCB's total suction instead of thermal resistivity is developed to estimate its degree of saturation.
- Using the results of researches done in the area of microbial activity at the DGR environment, in conjunction with highly compacted bentonite's electrical resistivity measurements, four plots (figures 4.14-14.17) are generated to estimate potential microbial activity near the waste bundles at the deep geological repository.

5.3 Future work

The following recommendations are proposed as potential future research directions in the field:

- Regarding the reviewed literatures, controversy result was found when relating hydraulic conductivity and electrical properties, which can be of interest for further investigation
- Similar approach to that of chapter 4 part 1 can be followed to govern a generalized relationship between electrical and thermal resistivity of highly compacted bentonite, when having a saline pore fluid.
- The current research can be extended to cover other barrier materials such as dense and light backfills.

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