Hydraulic, Thermal and Electrical Conductivities of Composite Soils

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The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Papers

Published papers

- Al-Moadhen, M.M., Clarke, B.G. and Chen, X., 2018. The permeability of composite soils. Environmental Geotechnics, pp.1-13.
- Al-Moadhen, M., Clarke, B.G. and Chen, X., 2017, September. Hydraulic conductivity of composite soils. In Proceedings of the 2nd Symposium on Coupled Phenomena in Environmental Geotechnics (CPEG2). Leeds.

Papers prepared to be submitted for publication

- Compression characteristics of composite soils
- The impact of soil composition on thermal conductivity
- Electrical conductivity of composite sand-clay soils at low water salinity

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Abstract

Composite or intermediate soils, that is soils that are formed of more than one category of soils, are commonly encountered either as natural soils on which engineered earth structures are built, or as reconstituted materials used for the processes of filling and stabilization in many engineering problems, e.g. in engineered liners and environmental barriers. These soils are often difficult to sample and test when using standard site investigation methods. The basic concept of composite soils is known, but, studies performed on these materials are limited. This research focuses on experimentally investigating the hydraulic, thermal and electrical conductivity of a wide range of composite sand-clay mixtures. The ultimate goal is to increase the understanding of the composite soils and to establish a coherent framework for supporting the design and construction of conductivity related projects by establishing correlations between soil's compositional and physical factors, and its conductivity.

Two new pieces of equipment were designed for the purposes of the study. The first piece of equipment was designed to comply with the assumptions of Terzaghi for one-dimensional consolidation to determine the hydraulic conductivity indirectly. The second one was designed to determine the hydraulic, thermal and electrical conductivities directly following the principles of Darcy, Fourier, and Ohm. Their design criteria, principles, and test methods are described in detail. Both sets of equipment were shown to be simple and effective and provided repeatable results which could be compared to data obtained from other laboratory investigations and published models.

Soils of known composition formed of five clay minerals and three types of sands were used to investigate the effect of compositional (e.g. clay/ sand content, clay mineralogy, particle size distribution, pore water composition) and physical (e.g. water content, porosity, dry density, confining stress) properties on the soil's conductivity.

The results on the composite soils reveal that such soils can be divided into matrix dominated soils in which the electro-chemical inter particle relationships of the clay content dominate the behaviour and clast dominated

soils in which the inter particle contact forces of the sand content dominate the behaviour. The transition zone between them depends on the sand to clay content ratio, the initial conditions, the confining stress at the point at which the property was determined, clay mineralogy, particle size distribution and shape. Under a consolidation pressure of up to 1280 kPa, the transition zone occurs when the sand content is between 58% and 85%. In hydraulic conductivity, it happens when the clay content is between 20 - 35 %. Data on the thermal and electrical conductivity shows that the transition behavior is not so well defined but it is the sand particles that dominate the mass behavior when its content exceeds 65 – 78%.

The concept of matrix and intergranular void ratios can be used effectively to describe the consolidation and hydraulic conductivity of composite soils. The results of the consolidation tests on sixty sand-clay mixtures show that increasing the clay content increases the compression index and reduces the hydraulic conductivity. There is a relationship between hydraulic conductivity of composite soils and void ratio. For matrix dominated soils, the relationship is a function of clay type (expressed by activity) and matrix void ratio; for clast dominated soils, it is a function of particle size and intergranular void ratio. However, the concept of the matrix and intergranular void ratios cannot be used to describe the thermal and electrical behavior of composite soils as there is no simple relationship with thermal and electrical conductivity.

Test results on thirty two saturated samples of composite soils show that the bulk thermal conductivity of soils can be determined from the soil's constituents (water, clay, sand) using the thermal conductivity of the individual solid particles and their volumetric fractions present in the whole soil based on the geometrical mean method. The results also indicate that the bulk thermal conductivity increases when the sand content increase, dry density increases, and water content decreases. At a constant heat flux, the increase in temperature in sands generally exceeded that for clays and the time needed to reach the maximum temperatures was shorter for sands than for clays which depend on the clay mineralogy and sand particle size.

The interpretation of the electrical conductivity of composite sand-clay soils demonstrates that the overall electrical conductivity in these soils can be modelled as a parallel function of two main components; bulk pore fluid

conductance and clay minerals conductance within the soil that are dependent on the conductivity of fluid and clay particle surfaces, respectively, and their volumetric fractions. Test data on thirty seven samples of composite sand-clay soils prepared with tap water of low electrical conductivity shows that, for the majority of the data, the clay conductance exceeds that of bulk water indicating the importance of clay in the process of current transfer through soils. A soil mixture prepared with tap water of low electrical conductivity having higher cation exchange capacity (*CEC*) and specific surface area (A_s) (i.e. bentonite) will display a higher electrical conductivity than a soil with lower *CEC* and A_s (i.e. kaolinite, sand) at the same porosity. The results also show that as the sand content increases the overall electrical conductivity decreases and there is either a direct or inverse correlation between the electrical conductivity and soil's porosity or water content that depends mainly on the interplay between the clay and water conductance.

By testing a wide range of soils of known composition (known clay, sand and water content and type), it has been shown that it is quite possible to correlate conductivity with the physical properties of the soil constituents and establish new conduction models based on the soil's compositional and physical properties.

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A	Cross-sectional area (m^2)
a	Diameter of stand pipe in falling head test (mm)
$A.$	Activity
A_s	Specific surface area (m^2/g)
B	Mobility of the cations ($S.cm^2\ meq^{-1}$)
C_c	Compression index
C_{c-g}	Compression index in terms of global void ratio
C_{c-m}	Compression index in terms of matrix void ratio
CEC	Cation exchange capacity (meq/g)
C_m	Percentage of clay by weight in the solid phase (%)
C_v	Volumetric fraction of clay in the solid phase
c_v	Coefficient of consolidation (m^2/year)
d_{10}	Effective particle size corresponding to 10% finer passing (cm)
e_g	Global void ratio
e_{g100}	Global void ratio at 100 kPa effective stress
e_i	Intergranular void ratio
e_L	Void ratio at liquid limit
e_m	Matrix void ratio
e_{max-f}	Maximum void ratio of fine grain
e_{max-s}	Maximum void ratio of sands
E_s	Electrical conductance of clay minerals (S/m)
E_w	Electrical conductance of bulk water in soils (S/m)
F	Formation factor
G_c	Specific gravity of pure clay
G_s	Specific gravity of sand
G_T	Specific gravity of the whole sample
I	Current (Ampere)
i_e	Electrical gradient
I_h	Hydraulic gradient
I_L	Liquid limit (%)
I_P	Plastic limit (%)
I_t	Thermal gradient
K	Intrinsic hydraulic conductivity (m/s)

k_a	Thermal conductivity of air (W/m ^{o}C)
k_{clay}	Thermal conductivity of clay grains (W/m ^{o}C)
k_{dry}	Thermal conductivity of soil in dry conditions (W/m ^{o}C)
k_e	Normalized Kersten's number
k_h	Hydraulic conductivity (m/s)
$k_{h\text{-}direct}$	Hydraulic conductivity measured directly from conductivity cell (m/s)
$k_{h\text{-}indirect}$	Hydraulic conductivity calculated indirectly from consolidation tests (m/s)
k_o	Thermal conductivity of other minerals (W/m ^{o}C)
k_q	Thermal conductivity of quartz (W/m ^{o}C)
k_s	Thermal conductivity of solid particles, minerals (W/m ^{o}C)
k_{sand}	Thermal conductivity of sand particles (W/m ^{o}C)
k_{sat}	Thermal conductivity of soil in saturated conditions (W/m ^{o}C)
k_t	Thermal conductivity (W/m ^{o}C)
k_w	Thermal conductivity of water (W/m ^{o}C)
L	Length of sample (m)
m	Archie cementation factor
m_v	Coefficient of volume compressibility (m^2/MN)
n	Porosity
n_i	Porosity based on intergranular void ratio
n_m	Porosity based on matrix void ratio
P_1	Inlet pressure to the cell (kPa)
p_d	Dry density (Mg/m^3)
PI	Plasticity index (%)
Q	Supplied power (heat flux) (W)
q_e	Current flow rate (Ampere)
q_h	Fluid flow rate (m^3/s)
q_t	Heat flow rate (W, J/s)
Q_v	Cations-concentration per volume (meq. cm^{-3})
R	Roundness
R	Resistance (Ohm)
r_s	Resistivity (Ohm. m)
S	Degree of saturation (%)
S_m	Percentage of sand by weight in the solid phase (%)
S_v	Volumetric fraction of sand in the solid phase
t_{50}	Time corresponding to the 50% primary consolidation (min)

t_{90}	Time corresponding to the 90% primary consolidation (min)
Δe	Change in void ratio
ΔH	Settlement, change in sample height (mm)
ΔT	Temperature difference (^{o}C)
μ	Permeant viscosity
V	Voltage (Volts)
V_c	Volume of clay (m^3)
V_s	Volume of sand (m^3)
V_T	Total volume of soil (m^3)
V_v	Volume of voids (m^3)
W_c	Water content (%)
x_a	Volumetric fraction of air in the whole soil
x_{clay}	Volumetric fraction of clay in the whole soil
x_q	Volumetric fraction of quartz in the solid phase
x_s	Volumetric fraction of solid particles in the whole soil
x_{sand}	Volumetric fraction of sand in the whole soil
x_w	Volumetric fraction of water in the whole soil
γ	Specific unit weight of permeant (kN/m^3)
γ_w	Unit weight of water (kN/m^3)
$\delta\sigma'_v$	Change in effective stress (kPa)
θ	Angle of friction
σ'_v	Effective stress (kPa)
σ_s	Electrical conductivity of clay particle surfaces (S/m)
σ_T	Overall electrical conductivity (S/m)
σ_w	Electrical conductivity of pore water (S/m)

Chapter 1
Introduction

1.1 General

In the classical approach to geotechnical engineering, soils are generally divided into four categories – very coarse, coarse, fine grained and organic soils. Classification of soils for engineering purposes uses these categories to describe soils by their principal fraction (e.g. sand, clay) which is modified by the percentage of the secondary fraction (e.g. sandy clay, clayey sand). However, most common natural deposited soils (e.g. alluvial soils, glacial tills, and residual soils) and artificial soils (e.g. engineered fills and environmental barriers) contain particles of different sizes and types that span more than one of these categories; that is many soils encountered are composite or intermediate soils.

Composite soils can be possibly defined as having a combination of engineering characteristics of fine-grained and coarse-grained soils. The interaction and arrangement of the fine and coarse particles in composite soils affects the engineering behaviour such that they can be expected to exhibit behaviours and modes associated with the fine and coarse soils. The nature of the inter-particle forces between coarse particles is different from the electrical-chemical interaction present between fine particles. These inter-particle forces affect soil macro behaviour, which, in geotechnical engineering is mostly limited to the mechanical characteristics. The general concept of composite soils is understood but research conducted on these materials is limited. This is evident from the fact that empirical correlations are commonly used in geotechnical engineering to allow for differences between observed behaviour and theoretical prediction. Design guidelines and analytical methods tend to refer to soils either as fine-grained soils or as coarse-grained soils based on their gradation only.

A key difference between fine and coarse soils is the hydraulic conductivity parameter, which ranges from (10^{-13} – 10^{-7} m/sec) to (10^{-6} – 10^{-3} m/sec) for clays and sands, respectively. Hydraulic conductivity is not only a distinguishing characteristic between fine and coarse grained soils, it is also one of the most important physical properties serving as a governing parameter in the practical design of many applications such as embankment backfill, hydraulic liners, and settlement of structures (Chapuis, 1990, Mollins et al., 1996, Komine, 2004, Yeo et al., 2005). The modern and efficient design of such structures requires an accurate value of the hydraulic conductivity to limit to a minimum detrimental fluid leakage, and, to control rate of settlement. Generally, hydraulic conductivity represents a measure of a soil capacity to transfer water or other fluids from one region to another through its interconnected pore spaces. The value of the hydraulic conductivity is not constant and depends on the characteristics of the permeant and soil properties such as the fabric and composition.

The ability of a soil to conduct fluids has been studied for a number of years but, more recently, interest in thermal and electrical conductivity has increased substantially due to the rapid growth in their relevant engineering applications. Thermal conductivity has been proven to have a profound effect on controlling the mechanism of heat transfer into/from a soil (Brandl, 2006, Gori and Corasaniti, 2013, Nikolaev et al., 2013, Alrtimi et al., 2014). It influences a soil's behaviour in some engineering applications such as energy piles, and ground source heat pumps. The range of differences in the value of the thermal conductivity from coarse to fine soils is regarded as small compared to that for hydraulic conductivity. Nevertheless, it varies within one to two orders of magnitude ranging from (0.25 – 4.5 W/m ^{o}C) depending on the soil composition and its physical properties.

Electrical conductivity of soils can be used as a useful indicator for determining their moisture content (Lovell, 1985), total dissolved salts (Corwin and Lesch, 2005); salinity (Rhoades et al., 1989); and also used in the construction process of poor and unstable fine-grained soils based on the applications of electro-osmosis (Hamir et al., 2001, Mitchell and Soga, 2005). The majority of research on electrical conductivity has concentrated on either pure coarse soils, i.e. sands and sandstones, or shaly sandstones containing low amount of clay and, thus, most models do not include the effect of clay type and amount properly. In composite soils, particularly those with a high clay content, clay particles constitute an additional path for current to transfer from one region to another making the interpretation of the electrical conduction in composite soils more complicated.

1.2 Soil conductivities and their common analogies

It has been shown that the flow of fluid, heat and electricity through a soil is driven by a similar process during its transfer or travel from one region to another in that the rate of flow, J_i, correlates directly to its corresponding driving force F_i, as follows:

$$J_i = L_i * F_i \qquad (1.1)$$

where L_i is the coefficient of conductivity for flow. This common relationship can be expressed according to each phenomenon of flow:

Fluid flow	$q_h = k_h i_h A$	Darcy's Law
Heat flow	$q_t = k_t i_t A$	Fourier's Law
Electricity flow	$q_e = \sigma_T i_e A$	Ohm's Law

where q_h, q_t, and q_e are the fluid, heat, and electrical flow rates, respectively. Coefficients k_h, k_t, and σ_T are the hydraulic, thermal, and electrical conductivity, respectively. Figure 1.1 shows the three types of flow in a soil (Mitchell and Soga, 2005).

As long as the flow flux and potential are linearly correlated, the theoretical and mathematical expressions of each flow is similar and the models for one type of flow might be used to analysis another type of flow. Hence, all soil conductivities are expected to be influenced by similar factors, compositional, physical and environmental factors. The analogy is discussed further in chapter two. The relationships, dependency and applications of soil conductivities are summarized in Table 1.1.

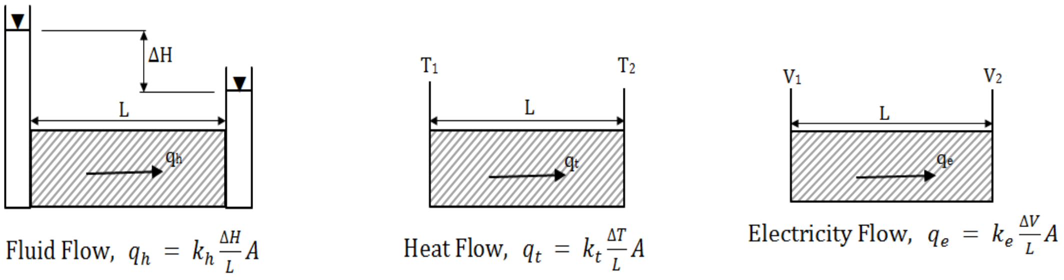


Figure 1.1: Three types of the direct flows in a soil (Mitchell and Soga, 2005).

Table 1.1: The relationship, dependency and applications of soil conductivities

Conductivity	Relationship	Dependency	Applications
Hydraulic conductivity (k_h)	Potential: total head (h) Conduction: $q_h = k_h i_h A$ Darcy's Law Gradient: $i_h = -\frac{dh}{dx} = \frac{\Delta h}{L}$	• Compositional: Nature of permeant, particle size distribution (PSD), particle shape and texture, mineralogical composition • Physical and environmental: void ratio, degree of saturation, soil fabric (structure), temperature, and effective stress	• Geotechnical: excavation in water-bearing ground, estimation of earth dams and embankments seepage flow, preventing of piping and erosions, analyses of highway and airfield bases and sub-bases, and control the rate of structure consolidation. • Environmental: design of disposal waste facilities, hydraulic barriers (slurry walls), waste ponds, and mine tailings ponds. • Agricultural: construction of irrigation ditches, canals and water reservoirs.
Thermal conductivity (k_t)	Potential: temperature (T) Conduction: $q_t = k_t i_t A$ Fourier's Law Gradient: $i_t = -\frac{dT}{dx} = \frac{\Delta T}{L}$	• Compositional: particle size distribution (PSD), particle shape and texture, mineralogical composition • Physical and environmental: moisture content, density, porosity, stress, degree of saturation, and temperature	• Geotechnical: heat ground enhancement techniques, design of ground-source heat pump system (GSHPS) and thermal energy piles, design of cold and hot pipes in unfrozen soils. • Environmental: Maintaining of heating and cooling of buildings, underground power cables, design of disposal sites and buffer for nuclear or municipal waste.
Electrical conductivity (σ_T)	Potential: voltage (V) Conduction: $q_e = \sigma_T i_e A$ Ohm's Law Gradient: $i_e = -\frac{dV}{dx} = \frac{\Delta V}{L}$	• Compositional: particle size distribution (PSD), electrical conductivity of pore water, mineralogical composition of particles • Physical and environmental: moisture content, density, porosity, stress, degree of saturation, and temperature	• Geotechnical: Dewatering of sludges and slurries, fine soils stabilisation and remediation using electrosmosis principles, improving friction pile capacity, stabilisation of slopes and embankment, and soil consolidation and drainage. • Environmental: dissolution and or removal of contaminants from soils, geophysical explorations. • Agriculture: assessment of soil salinity, mapping and quality.

1.3 Study aims and objectives

The central focus of the study was to investigate the hydraulic, thermal and electrical conductivities of a wide range of composite soils under controlled conditions to develop an understanding the effect of a soil composition and physical properties have upon the conductivity to determine when a composite soil behaves as a clay-dominated or sand-dominated soil. The main motivation behind this was to develop a coherent framework for supporting the design and construction of geotechnical projects. The study comprises some aims that can be achieved by a variety of objectives:

1. Review the previous studies concerning soil's conductivity in the world of geotechnical engineering by:
    a. Gaining a thorough understanding of soil conductivities and determining the methods used to assess them and the factors that influencing them.
    b. Establishing the most useful methods to predict soil conductivity.
    c. Identifying gaps or limited knowledge in soil conductivity that require further investigations.

2. Assess the behaviour of clay-dominated and sand-dominated composite soils in consolidation so that an indirect assessment of the hydraulic conductivity can be made and the transition from clay dominated to sand dominated soil be established by:
    a. Designing a new consolidation cell that allows fully saturated samples of composite soils to be tested.
    b. Performing series of experiments on various samples of the composite soil to measure their compressibility characteristics, and the variation of hydraulic conductivity with void ratio/density.
    c. Determining the sand/clay content at which the transition zone occurs and the factors that affect it.

3. Assess directly the hydraulic, thermal and electrical conductivities of soils of varying compositions by:
    a. Designing a single integrated cell (a conductivity cell) that allows saturated soil samples of varying compositions to be consolidated.

    b. Undertaking constant head tests to directly determine the hydraulic conductivity of the soils at different densities/void ratios.
    c. Using steady-state method to directly determine the thermal conductivity of the soils at different densities/porosities.
    d. Carrying out electrical tests to measure the electrical conductivity of the soils at various densities/porosities.

4. Examine the relationships between hydraulic, thermal and electrical conductivities of soils and their compositional and physical properties by:
    a. Validating the existing relationships for the hydraulic, thermal and electrical conductivities of soils with their physical properties using the measured results.
    b. Establishing new empirical and semi-empirical models for hydraulic, thermal and electrical that are based on soil's composition and physical properties.
    c. Proposing a means of determining the hydraulic, thermal and electrical conductivities of soils from their physical properties.

1.4 Structural organisation of thesis

The thesis includes seven chapters;

Chapter 1: this chapter provides a general background to the topic, and states the aims and objectives of the research.

Chapter 2: is a literature review to introduce the composite soils and their physical characteristics, and comments on studies that have investigated their hydraulic, thermal and electrical conductivities. This chapter concentrates on the general fundamental concepts of the mechanism of flows through soils and their corresponding conductivities; hydraulic, thermal and electrical. The definitions and principles of flow, the compositional, physical and environmental factors that affect flow, and the methods used to determine each of these conductivities are presented.

Chapter 3: begins with a description of the materials used to form the composite soil mixtures that were used in the research. The equipment used and test procedures for determining the hydraulic, thermal and electrical conductivity of composite soils is presented. Two new pieces of equipment were designed. The first one, the consolidation equipment, was designed for assessing, indirectly the hydraulic conductivity using a soil's consolidation characteristics. The second piece of equipment, the conductivity equipment, was designed to determine the hydraulic, thermal and electrical conductivity directly. Details are given of the operational criteria and design principles, control requirements, components used in the equipment, sample preparation, testing procedures and methods of interpretation used to determine the coefficients of conductivity and their dependencies.

Chapter 4: presents the analysis and discussion of the consolidation and hydraulic conductivity properties of six-groups of composite soils consisting of four types of clays and two types of sands. The classification properties of all composite soil mixtures was used as a control to create saturated samples. The interpretation of the consolidation behaviour and characteristics of all composite soils are presented. The behaviour of clay-dominated and sand-dominated composite soils is expressed in terms of the properties of consolidation and hydraulic conductivity highlighting their relationships to the physical characteristics of the soils and the transition from clay dominated to sand dominated behaviour. At the end of this chapter, there is a comparison between hydraulic conductivity determined directly from flow through the new conductivity cell and that determined indirectly from consolidation tests.

Chapter 5: includes test results and their interpretation for thermal conductivity of composite soils made of varying percentages of clays and sands. The influence of the composition of the soil (water and solids), and the soils' physical properties (water content and dry density) have upon the thermal conductivity of composite soils is discussed. An evaluation of methods of predicting thermal conductivity values from published semi empirical and empirical models is undertaken. A more representative heat conduction model is introduced based on the thermal and volume properties of soil's constituents.

Chapter 6: in this chapter, tests results for electrical conductivity of composite sand-clay soils are presented. The effect of sand/clay content and clay mineralogy on the overall soil electrical conductivity are explored. The impact the pore water conductivity and clay surface conductivity have upon the overall soil electrical conductivity is investigated. This chapter presents some relationships between the overall electrical conductivity with porosity and water content in composite soils. The values of electrical conductivity derived from the tests on composite soils are compared to those predicted from two common electrical models and new models are developed to account for the effect of high clay content at low salinity.

Chapter 7: summarizes the conclusions drawn from this research and provides recommendations for future works.

Chapter 2

Literature Review

2.1 Introduction

The practical approach to geotechnical engineering is essentially based on an assessment of the engineering characteristics of either fine or coarse grained soils depending only on their particles gradation. However, most natural depositions and man-made fills contain varying amounts of both fine and coarse fractions in their profile, that is, most of them are composite or intermediate soils. Studies in the literature reviewed show that there is little research published on composite soils, particularly on the properties of hydraulic, thermal and electrical conductivities of soils.

This chapter begins with a brief description of composite soils, their basic characteristics, and the relevant previous studies conducted on their engineering properties. The dominant topics in this chapter are concentrated on presenting the general fundamental concept of the mechanism of flows through soils and their corresponding conductivities (hydraulic, thermal and electrical). The definitions, principles, the common factors influencing each of them, and the existing testing methods used to determine each of these conductivities are presented.

2.2 An introduction to composite soils

Soils can be defined as uncemented or weakly cemented depositions of natural aggregated-minerals that can be separated by moderate mechanical means, i.e. water agitation. Soils are generally divided into four categories – very coarse, coarse, and fine grained and organic. Classification of soils for engineering purposes uses these categories to describe soils by their principal fraction (e.g. sand, clay) which is modified by the percentage of the secondary fraction (e.g. sandy clay, clayey sand). However, most natural depositional soils and artificial soil mixtures contain particles of sizes and types that span more than one of these categories; that is many encountered soils are composite soils (Head, 1982, Omine et al., 1989, BS EN ISO 14688-2:2018).

The European soil classification scheme (BS EN ISO 14688-2:2018) uses a particle size of 0.06 mm as a boundary between coarse- and fine-grained soils (Figure 2.1a); the American scheme, more specifically the Unified Soil Classification System (ASTM D2487-17, 2017) considers 0.075 mm (Figure 2.1b). These fixed boundaries are limited when used with composite fine-coarse soils as the fine fractions in the soils are very likely to exhibit a wide range of plasticity. The influence of plastic fine fractions on soil's properties is not properly considered by the percentage of 50 used in the common classification schemes.

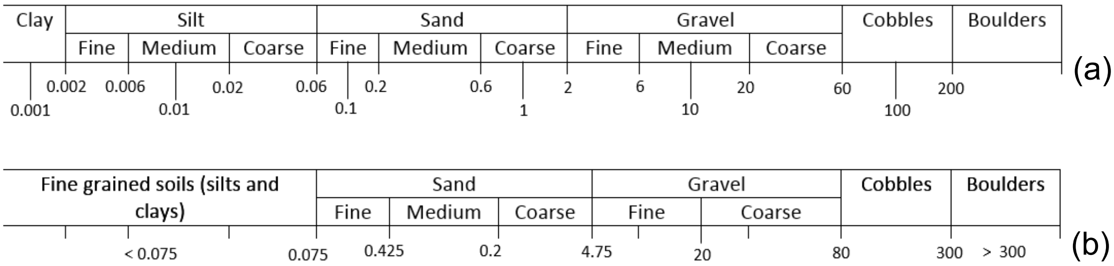


Figure 2.1: Soil classification based on the: (a) European scheme, (b) ASTM-USCS scheme

The boundary between fine- and coarse-grained behaviour in an engineering scheme is different to that used in the classification schemes and is not as clearly defined. For example, soils used for engineered fills (BS6031:2009) that contain at least 15% fines are described as cohesive soils and soils containing at least 35% fines are described as cohesive when designing cuttings and embankments. BS6031:2009 suggests that composite soils are those that contain at least 10% of the secondary fraction. BS 14688-2:2018 defines a composite fine soil as one in which the fines content determines the engineering behaviour. For example, a composite coarse soil is one which contains fines but behaves as a coarse-grained soil.

A full description of a composite soil should be based on both the classification scheme for engineering purposes and a scheme for engineering behaviour. Given the distribution of composite soils, studies on the behaviour of composite soils should provide a better understanding of how these complex soils behave.

2.3 A phase diagram for composite soils

In classical soil mechanics, most empirical correlations and theoretical frameworks for soil properties are based on void ratio, a density parameter, that refers to the ratio of volume of voids to the volume of solids. However, in the case of composite soils having two-solid phases, five density parameters have been used including global void ratio, matrix void ratio, intergranular void ratio, maximum void ratio and relative density.

The global void ratio (e_g) does not take into account the influence of the matrix upon the permeability of sandy clays or the intergranular structure of clayey sands. Mitchell (1976) introduced the concept of the matrix void ratio, e_m, a function of the coarse grained particles within a composite soil matrix. If the sand content in a soil is relatively small (Figure 2.2a), the global behaviour of the soil will be controlled by the electrochemical inter-particle forces existing among clay-fine grains. The coarse particles are inactive because they are not in contact with each other.

It is the properties of the clay content that govern the behaviour of a matrix dominated soil. The matrix void ratio, e_m, (Figure 2.3b) is represented by the volume of voids (V_v) and the volume of clay(V_c):

$$e_m = \frac{V_v}{V_c} \qquad (2.1)$$

$$e_m = \frac{e_g}{C_v} = \frac{e_g}{(1 - Sv)} \qquad (2.2)$$

Where C_v and S_v equal the volumetric fraction of dry solids occupied by the clay and sand grains, respectively, in the mixture. This can be expressed in terms of the weight of particles S_m:

$$e_m = \frac{e_g}{\frac{G_T}{G_C} * (1 - S_m)} \qquad (2.3)$$

Where G_T is the specific gravity of the whole mixture (the global); G_c is the specific gravity of clay grains.

As the sand content increases, force chains start to develop (Figure 2.2b) between the sand particles until the soil behaviour becomes dominated by the structure of the sand particles (Figure 2.2d). Thus, there is a transition zone, Figure 2.2c, when the soil has characteristics of both a fine grained and coarse grained soil. The limits to this zone could be defined by the maximum void ratio of sand grains, $e_{max\text{-}s}$ (Omine et al., 1989), at which the loosest state of the sands occurs when the sand particles have just made contact; and the maximum void ratio of fines, $e_{max\text{-}f}$ (Thevanayagam, 1998), when the fine particles are no longer in suspension within the soil mixture. The maximum void ratios; $e_{max\text{-}s}$ and $e_{max\text{-}f}$, represent the reference void ratio of a pure sand and pure fine soil, respectively, at the minimum index density/unit weight (ASTM D4254 – 16).

When the void ratio between the sand particles is less than the maximum void ratio of those particles, the sand fraction controls the mechanical behaviour of the soil since the fine grained particles filling the voids between sand particles have a limited effect. A composite soil may respond as a coarse grained, or sandy soil (Figure 2.2d). In such case, a more relevant density parameter, the intergranular void ratio, e_i, (Figure 2.3c) may be used:

$$e_i = \frac{V_v + V_c}{V_s} \qquad (2.4)$$

Where V_v, V_c, V_s are the volume of voids, clay, and sand, respectively. This can be expressed in terms of the global void ratio (e_g) and sand content (S_v or S_m) then:

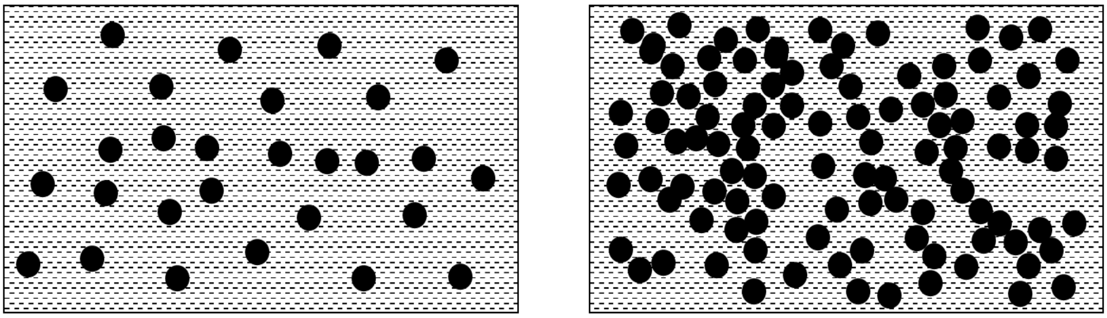
$$e_i = \frac{e_g + C_v}{S_v} = \frac{e_g + \frac{G_T}{G_c} * (C_m)}{\frac{G_T}{G_s} * (S_m)} \qquad (2.5)$$

Georgiannou et al. (1990), Lupini et al. (1981), Mitchell James (1993), Pitman et al. (1994), Lade et al. (1998), Thevanayagam (1998), Salgado et al. (2000), Chu et al. (2003) used the intergranular void ratio (e_i) to characterize the shear strength properties of composite clayey sands. Others (e.g. Fear and McRoberts, 1995, Lade and Yamamuro, 1997, Boulanger et al., 1998, Yamamuro and Lade, 1999, Salgado et al., 2000, Yamamuro and Covert, 2001, Thevanayagam and Martin, 2002, Xenaki and Athanasopoulos, 2003) have used the concept of the intergranular void ratio in the assessment of the liquefaction potential of soil mixtures.

In the present study, the concept of the matrix and intergranular void ratios have been used in the interpretation of the data of consolidation, hydraulic, thermal and electrical conductivity of composite soils in chapters 4, 5, 6, 7. The main objective of using them was to assess their usefulness and applicability in the data analysis processes.

Phase 1A clay dominated composite soil with no force chains between sand particles

Phase 1B clay dominated composite soil with force chains developing between sand particles



Phase 2 (transition) composite soil with force chains between sand particles starting to dominate

Phase 3 sand dominated composite soil with majority of force being transmitted through the sand particles

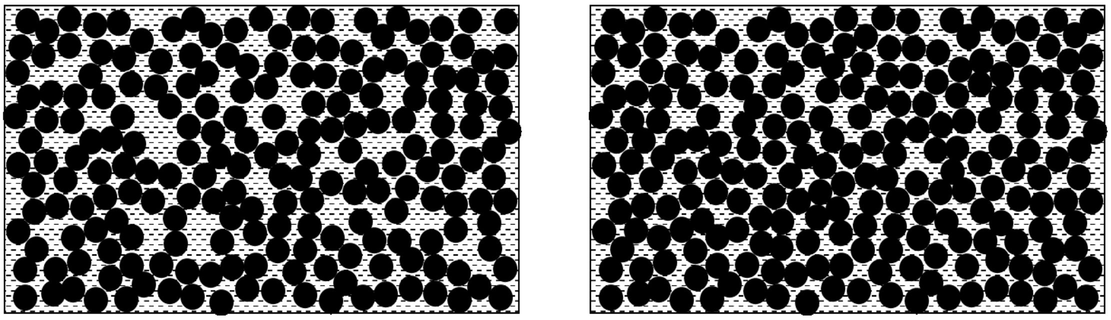


Figure 2.2: The effect of sand content on the behaviour of composite soils

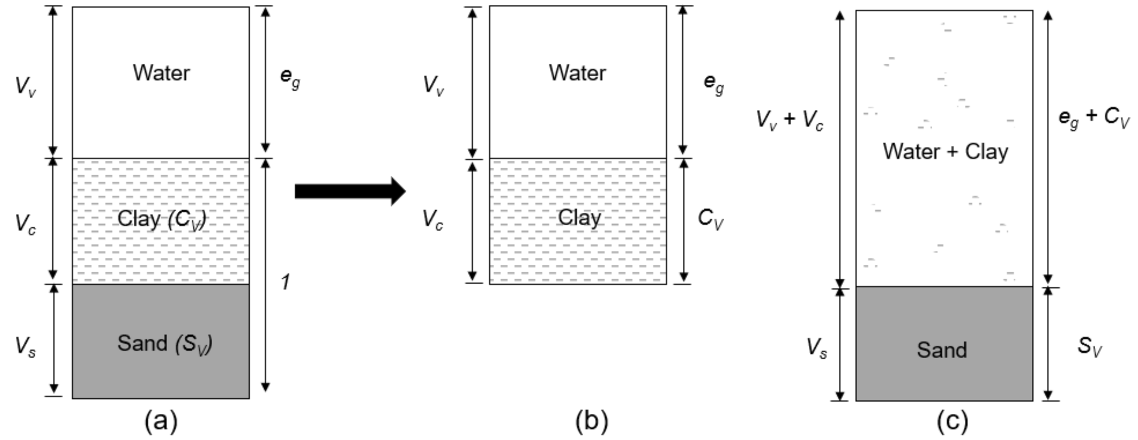


Figure 2.3: Phase-diagrams of: (a) saturated composite soil; (b) fine-grained soil; and (c) coarse-grained soil.

2.4 Engineering properties of composite soils

2.4.1 Index properties

Consistency limits are important in identifying and classifying soils, especially fine-grained soils. They are regarded as the basis for primary assessment of a wide range of mechanical, hydraulic, thermal and electrical properties of soils.

In terms of composite soils, early works on consistency limits, particularly liquid limit, were carried out on clays with fine and medium sands. For example, Seed et al. (1964) studied the effect of sand content on the liquid limit of kaolin, illite and montmorillonite clays. They showed that the existence of sand particles smaller than 425 um in mixtures will result in a reduction of the liquid limit in a linear relationship (in proportion with the sand content) provided that the clay content is more than 10% for inorganic clays and 20% for organic clays. Dumbleton and West (1966) used four types of coarse fractions; angular glass fragments, spheres of glass, angular quartz fragments and flaky particles to assess their influence on the value of the liquid limit. They found that a linear relationship is applicable only with mixture of glass spheres, and that the smaller size of coarse grains caused larger influence on the liquid limit than the larger particles because of their higher specific surface area. Sivapullaiah and Sridharan (1985) measured the consistency limits of a range of bentonite mixed with sand of particles smaller than 425 um using the cone penetrometer and Cassagrande methods to conclude that the limits of composite mixtures are not totally governed by a linear relationship with sand content and the value from the penetrometer test is generally less than that obtained by the Cassagrande method. Tan et al. (1994) assessed the effect of sands having medium particles on the liquid limit of marine clays, montmorillonite and kaolinite clays. They proposed a different linear relationship depending on whether using clay or silt fractions in the composite mixture and concluded that the linear relationship is valid up to sand content of up to 60% in the mixture. Bera (2011) also investigated the influence of fine sand content on consistency characteristics of composite sand-clay soils. The results revealed that both liquid and plastic limits of the soils decrease with an increase in the percentages of sand in an approximate linear relationship.

The above review shows that in most studies, the liquid and plastic limits decrease with sand content for a given clay type, and this reduction is linearly related to the sand content. In this study, it is a good practice to assess the extent to which a similar relationship applies to composite soils with different type and content of clays and sands.

2.4.2 Mechanical properties

Previous studies have generally concentrated on the consolidation and shear strength of clayey or silty sands with clay content up to 40%, a particular case of composite soils.

The majority of the studies on consolidation aimed to assess when the coarse grained particles or clay minerals dominate the behaviour of the whole mixture, and what possible parameters control the transition boundaries under the process of consolidation and shear strength. For example, Hight et al. (1994) carried out consolidation tests on Ham River sand-kaolinite mixtures and reported that the consolidation properties of the mixtures tend to be governed by the compressibility of the sand with kaolin content of up to 20%. Kumar and Wood (1999) noted that for a clay content greater than 35%, it is the kaolin matrix that dominated the compression behaviour of the kaolin-gravel mixture. Thevanayagam (1998) suggested that, if the fines content in a silty sand is greater than 30%, the soil could behave as silt attributing that to the plasticity and particle size of silt. Salgado et al. (2000) reached a conclusion that it is the sand phase that entirely governs the shear strength of clay–sand mixtures for a sand percentage greater than 80%. Nevertheless, Leroueil and Hight (2003) stated that the effect of fine fractions on consolidation of a sandy soil is generally limited. More recently, Monkul and Ozden (2007) used one dimension compression tests on a mixture of kaolin-sand with kaolin content up to 40%, to show that the transition from fine grained to coarse grained behaviour occurs between 19% and 34% fines content depending on the initial void ratio and confining stress. Later, Cabalar and Hasan (2013) studied the effect of particle sizes ranging from fine clay to coarse sand and the shape of the sand particles with different pore fluids. The results suggested that sand with lower roundness (R) and sphericity (S) values exhibits higher compressibility.

The shear strength property of composite sand-clay soils has been explored by several researchers focusing on the role of addition of fine fractions on the behaviour of coarser fractions. For instance, Kenny (1977) carried out an investigation on mixtures of crushed granular quartz with different clay types (i.e. kaolinite, chlorite, illite, montmorillonite) to show that the volumes of granular- and clay- minerals controlled the residual strength of the mixtures, and once the volume of granular content exceeds 50%, the strength is totally governed by these granular particles. Nakase and Kamei (1983) indicated that the angle of friction (θ) related to the undrained shear of natural marine clays of different plasticity mixed with different content of Toyoura sand is constant irrespective of plasticity variations. Skempton (1985) concluded that if the fraction of clay minerals exceeds 50% in the sand-clay mixtures, the shear strength is mostly dominated by sliding friction along clay grains, and when the percentage is decreased to less than 25%, the soil tends to behave in a manner more similar to that of clean sand. Georgiannou et al. (1990) came to a conclusion that the matrix clay has a small effect on the friction angle of the coarser particles if its amount is less than 20% in the mixture. Similarly, Vallejo and Mawby (2000) found that the shear strength response of composite sand-clay mixtures will be entirely governed by the coarse sand particles content when the fines content is no more than 25%. Thevanayagam and Martin (2002) pointed out that if the fines content in a silty sand soil is greater than 30%, the soil behaves as a silt and the shear strength would be very sensitive to the existing fine content.

Clearly, the transitional behaviour between clay- (matrix) and sand- (clast) dominated composite soils under consolidation and shear strength is not clearly defined and is not a step change. The boundaries of the transition zone could depend on the particle size distribution, the clay mineralogy (e.g. Yin, 1999, Nakase and Kamei, 1983) and particle shape (e.g. Cabalar and Hasan, 2013).

2.4.3 Hydraulic, thermal and electrical properties

The most significant influence of the addition of clays to sands or even gravels is on the hydraulic conductivity parameter because it can change the behaviour of the soils from drained to partially-drained or even to undrained when subject to short term monotonic load. Hydraulic conductivity is used in the design process to predict the time for settlement to take place, as a control parameter in engineering specifications for compacted landfills consisting of sand-clay mixtures such that the hydraulic conductivity should be less than 10^{-9} m/s ensuring a high stability and performance (Mollins et al., 1996), and to predict flow into excavations. Hydraulic conductivity exhibits a range of more than 10 orders of magnitude from coarse sands to fine clays.

Permeability characterisations of composite sand-clay mixtures have been examined in a number of studies. The focus was mainly on compacted sand-bentonite and -kaolinite mixtures because of their importance in a number of engineering structures (e.g. in engineered barriers and liners), ignoring the other types of mixtures (e.g. sand-illite mixtures) even though they exist in nature. Kenney et al. (1992) performed direct permeability measurements on compacted sand-bentonite mixtures with sodium bentonite of up to 20% to conclude that the permeability is highly dependent on the bentonite plasticity and its distribution in the mixtures. Mollins et al. (1996) found, from direct and indirect measurements of hydraulic conductivity of compacted sand-bentonite mixtures with bentonite content up to 20%, that the bentonite reduces significantly the hydraulic conductivity of sand and the size of the coarse fractions control its limits. Kumar and Wood (1997) conducting indirect assessment of the hydraulic conductivity using one-dimensional consolidation tests on coarse sand-kaolin mixtures showed that there is a unique relation for all soils containing kaolin content higher than 30% when using the matrix void ratio. Sivapullaiah et al. (2000) investigated the effect of the ratio between the sand fraction in sodium bentonite/sand mixtures on hydraulic conductivity to show that when the percentage of sand is sufficient, the active role of the bentonite is secondary and could be ignored, and so, the hydraulic conductivity could be controlled predominantly by the particle size of the sand. Belkhatir et al. (2013) came up with a conclusion that the hydraulic conductivity of sand-silt mixtures with silt content of 50% is smaller than that of the clean sand by four orders of magnitude and the intergranular void ratio is a good parameter to explain the behaviour.

The available research on the effect of clay type and content on thermal and electrical conductivity of soils in literature is very limited. In terms of thermal conductivity, Brigaud and Vasseur (1989), in one part of their study, investigated the effect of quartz and clay content on saturated samples of sandstone and kaolinite to show that the bulk thermal conductivity of the samples increases with increasing quartz content and decreases when increasing clay content in a nonlinear relationship attributing that to the thermal conductivity of the dominating solid particles. Beziat et al. (1992) studied the impact the sand and graphite particle sizes have upon the thermal conductivity of compacted smectite clays to find that the granulormetric distribution of sand and graphite particles in the mixtures has an essential role in enhancing the value of the thermal conductivity. Zhang et al. (2015) carried out an investigation on three types of sands, silica, Ottawa and graded sands, to study the effect the fine sand content has on the coarse sands. The results demonstrated that as the fine sand content increases, the bulk thermal conductivity of coarse sands at first increases to a maximum and then decreases which mainly depend on the soil density that related directly to the sand mineralogy. Similarly, Yu et al. (2016) used compacted mixtures of sand and kaolinite with kaolin content up to 20% to assess their thermal conductivity. The findings showed that as kaolin content increased, the thermal conductivity of the mixture increases to the critical kaolin content of 10%, the peak value, and then decreases

For electrical conductivity, the majority of studies have conducted for the petrochemical industry, focusing on either pure coarse soils, i.e. clean sands and sandstones, or shaly sandstones containing a low amount of clay (e.g. see Waxman and Smits, 1968, Bussian, 1983, Sen et al., 1988, Revil et al., 1998, Tenchov, 1998, Glover et al., 2000). This means that the effect of intermediate to high clay content has not been considered properly in the developed models, in particular in case where water of low electrical conductivity is used. Recently, Choo et al. (2016) have investigated the electrical conductivity of consolidated sand-kaolinite mixtures with varying pore water conductivities. They concluded that the electrical conductivity increases as the kaolin content increases in mixtures prepared with pore water with low electrical conductivity and the effect of kaolin was insignificant in the case of high water conductivity.

Overall, it can be said that most studies on a composite soil’s hydraulic, thermal and electrical conductivity, are generally focused on a particular type of mixture, i.e. sand-kaolinite or bentonite mixtures, ignoring the other types of composite soils even though they exist in nature. Also, the focus was essentially on mixtures with limited clay content. The effect of different types and contents of clays on conductivity has not been covered systematically, specifically for thermal and electrical conductivity.

2.5 Flow of water through soils

Soils are known as a permeable porous media due to the presence of interconnected pores by which any fluid (i.e. water) has the ability to pass and travel from regions of high energy to those of low energy.

The flow phenomenon of fluids in soils was first explored and quantified by Henry Darcy in France in 1856. Darcy (1856) relied on clean sand filter beds in his experiments to assess the rate of water flow using different heads at the top and bottom of the samples. The schematic diagram of his device setup is shown in Figure 2.4.

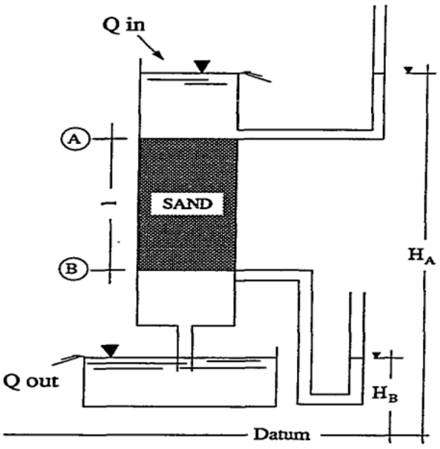


Figure 2.4: Schematic diagram setup of Darcy's device

Darcy developed an empirical law based on the large amount of his data in the form of:

$$q = k_h iA = k_h \frac{\Delta h}{L} A = k_h \frac{h_A - h_B}{L} A \qquad (2.6)$$

Where: q = Rate of flow in (m^3/min)

I = hydraulic gradient or difference in (m/m)

L = length of the sample between the points (A) and (B) in (m)

A = cross-sectional area of sample normal to the direction of flow (m^2)

In the equ. (2.6), Darcy stated that the rate of water flow through soils is directly proportional to the driving hydraulic head difference. Darcy's law is regarded as one of the most important principles in soil mechanics where flow of fluids is of concern. All steady state analyses and transient flow expressions in soils are dependent on Darcy's law because the flow is laminar.

During the 163 years since H. Darcy proposed his work on the flow of water through a hydraulic system, his empirical law has been subjected to a critical evaluation by several researchers using varying soils, fluids, test apparatuses and conditions (e.g. Scheidegger, 1957, Lambe and Whitman, 1969, Olson and Daniel, 1981). They showed that Darcy's law has solid evidences for different flow modes in different soils ranging from coarse sands to silts indicating its validity. However, others researchers (e.g. Lutz and Kemper, 1959, Miller and Low, 1963, Mitchell and Younger, 1967) have reported a deviation in the Darcy's law in others soils with very extreme particle sizes (i.e. clays and gravels).

2.5.1 Hydraulic conductivity

The hydraulic conductivity, k_h, is the only parameter of significance in the classical approach of soil mechanics that displays such a wide range of values. The difference in the hydraulic conductivity between coarse and very fine soils is up to ten orders of magnitude (see Table 2.7). Not only this, but also for a given soil, k_h differs over a great range depending on the value of void ratio of the soil.

The sustainable success of many engineered structures (i.e. liners and landfills) depends mostly on the hydraulic conductivity value. To maintain the critical level of the hydraulic conductivity of the structure and to reach the proper specification of the internal flow with a high performance integrity, usually composite soils (i.e. mixtures of sand-clay) are used. Characterisation of these materials to understanding their behaviour is, therefore, of high importance. In this research, a range of composite soils of varying particle size and composition were used in the measurement of hydraulic conductivity to assess how the type and content of sand/clay can affect the hydraulic conductivity.

2.5.2 Factors influencing hydraulic conductivity of soils

Flow of fluids in soils occurs along very complex and tortuous pathways through a chain of inter-connected pores of different type and sizes. Therefore, it is expected that the overall flow is a function of the volume and size distribution of the available pores which, because of their arrangements, depends on the density, saturation and the fabric of the soil.

All factors that influence the coefficient of hydraulic conductivity can be divided into three wide categories; compositional, environmental and those associated with the testing methods and measurements. The environmental factors can be managed and measured externally (i.e. water content, density, porosity, effective stress, and temperature), whereas the compositional factors are those that are associated with the soil particles themselves (i.e. minerals composition and particle size distribution). The methods and conditions of a test can also affect the value of hydraulic conductivity. In the following sections, some of these factors are briefly presented.

2.5.2.1 Compositional factors

The shape, size distribution and type of soil particles have an important role in influencing a range of the soil's geotechnical characteristics, particularly the hydraulic conductivity. The density and the internal structure of soils are mostly influenced by the critical skeleton arrangement of the particles that is linked directly with their external shapes. For a given stress and water content, the density of a soil formed of a range of particle sizes tends to be greater than that of a more uniform particle size distribution because the smaller grains fill the pore spaces between the larger particles in the more well graded soil. As the hydraulic conductivity decreases with increasing soil density, it is expected that soils with non-uniform particle sizes have lower permeability than those containing uniform grain sizes.

The hydraulic conductivity can also be influenced by the size of individual particles. The larger the particle sizes, the larger the pore spaces, and the higher the hydraulic conductivity. This can be seen more clearly in granular soils having more equidimensional particles and less variations in fabric. In granular soils, the finer particles have the most critical effect on the permeability. This is why Hazen (1892) used the effective particle size of 10% finer in proposing his hydraulic model for coarse-grained soils.

In fine-grained soils, the composition of the minerals forming the particles has the greatest effect on the flow of water through the soils. Smectite, illite, and kaolinite are the most common types of minerals in most natural deposited clays. These three different minerals retain on their particle external surfaces an adsorbed water layer of different thickness that can affect the water flowing through the pore channels. The thickness of the adsorbed water around particles is primary a function of the particle size. The smaller the particle size, the thicker the adsorbed water layer thickness. Given that smectite has the smallest particle size and kaolinite has the largest particle among clay minerals, it is expected that for a specific void ratio, the hydraulic conductivity of smectite is much lower than that in kaolinite. The confirmation of this argument is presented more clearly by Mesri and Olson (1971b) in Figure 2.5.

In line with this discussion, the present study assesses how different types and percentages of clays and sands affect the coefficient of hydraulic conductivity of composite soils.

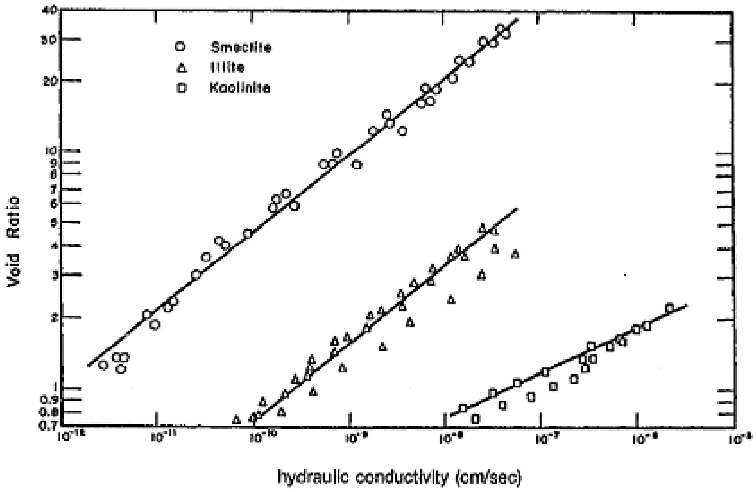


Figure 2.5: The variation of hydraulic conductivity with void ratio for smectite, illite and kaolinite clays (after Mesri and Olson, 1971b).

2.5.2.2 Environmental factors

In this section, the environmental parameters including type of permeant, void ratio, saturation, water content, stress and temperature that cause a change in the hydraulic conductivity are presented briefly.

2.5.2.2.1 Type of permeant

A wide range of permeants can be used in the experimental tests of hydraulic conductivity. These permeants differ in their compositional nature, physical and chemical properties, and any change in these properties can cause a change in the value of the hydraulic conductivity. The magnitude of the effect is more noticeable in fine-grained soils (i.e. in clays) that have inherently negative charges on their surfaces.

Among all the physical properties, the viscosity and unit weight of permeating fluids have the most influence on the flow of water through soils. A change in some of environmental factors (e.g. temperature) can alter the viscosity and density of soil fluids. Therefore, the hydraulic conductivity (k_h) is defined using the studies of Poiseuille as:

$$k_h = K.\ \frac{\gamma}{\mu} \tag{2.7}$$

Where K is the intrinsic hydraulic conductivity independent of the permeant, γ is the specific unit weight of permeant, and μ is the permeant viscosity.

The impact of the chemical properties (e.g. electrolyte concentration, pH) on the hydraulic conductivity has been of interest, and a number of investigations have been performed to assess it. Extensive discussions on the effect of different chemical properties on the permeability of clayey soils was given by Madsen and Mitchell (1989), and Fernandez (1989). A summary of the effect of the permeant chemical properties on the hydraulic conductivity is shown in Table 2.1.

Table 2.1: The influence of change in chemical permeant property on the hydraulic conductivity of soils

Permeant property	Change in property	Effect on hydraulic conductivity
Anion adsorption	↗	↙
Cation valence	↗	↗
Dielectric constant	↗	↙
Electrolyte concentration	↗	↗
pH	↗	↙

The amount of dissolved air in a permeant fluid also has an effect on the flow of water. A series of air bubbles can form in the narrow paths between the soil particles, which impede the flow of water through these paths providing an underestimate of the actual hydraulic conductivity. Thus, de-aired water was used in the measurement of hydraulic conductivity in this research.

2.5.2.2.2 Void ratio

Void ratio is the most important parameter in the determination of hydraulic conductivity of soils as it is directly connected to the size of the internal pore spaces where the water flows. For any soil, as the void ratio decreases, the hydraulic conductivity decreases.

A great range of studies have been conducted on natural and reconstituted fine and coarse grained soil samples and different empirical, semi-empirical relationships and theoretical expressions covering the effect of the global void ratio have been established (see Table 2.3). In composite soils consisting of two-solid phases, the matrix and intergranular void ratios are better indicators than the global void ratio in describing the hydraulic conductivity parameter because they are capable of determining to what extent the clay phase dictates or dominates the hydraulic conductivity behaviour of the whole soil mixture. This is discussed more in chapter 4.

2.5.2.2.3 Saturation

The presence of air in bubbles or dissolved in the pore fluid impedes and prevents the flow of fluids and reduces the hydraulic conductivity. Thus, the lower the soil saturation, the lower the hydraulic conductivity. The relationship between hydraulic conductivity and degree of saturation is more important in applications where the soil be in partially saturated conditions (i.e. in landfills, liners … etc). An example of the variations of hydraulic conductivity with degree of saturation is illustrated in Figure 2.6.

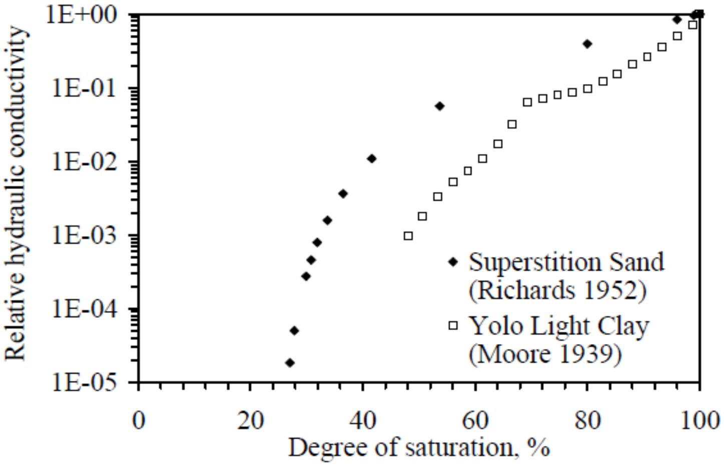


Figure 2.6: Hydraulic conductivity vs degree of saturation relationship.

2.5.2.2.4 Effective stress

When loads are applied on compressible soils, the volume of pore spaces available for water to flow is decreased, and consequently, the permeability decreases. Thus, it is reasonable to say that the hydraulic conductivity of soils is a stress-dependent parameter. The correlation between vertical effective stress and hydraulic conductivity has been demonstrated by many researchers (e.g. Tavenas et al., 1983a, Daniel, 1994, Mollins et al., 1996, Al-Moadhen et al., 2017, Al-Moadhen et al., 2018).

2.5.2.2.5 Temperature

As discussed in section 2.5.2.2-1 and shown in equation 2.7, the hydraulic conductivity, in some instances, is governed by the viscosity of soil fluids that is changed by the variation in temperatures. Olson and Daniel (1979) explored the effect of temperature on the hydraulic conductivity of three types of fine-soils prepared with distilled water (shown in Figure 2.7), and concluded that the viscosity is insensitive to conditions of low and moderate temperatures. However, for relatively high temperatures, an increase in temperature by one degree Celsius causes the viscosity to decrease by nearly 3%. Thus, the measured hydraulic conductivity at a given temperature should be corrected to the standard temperature of (20 °C).

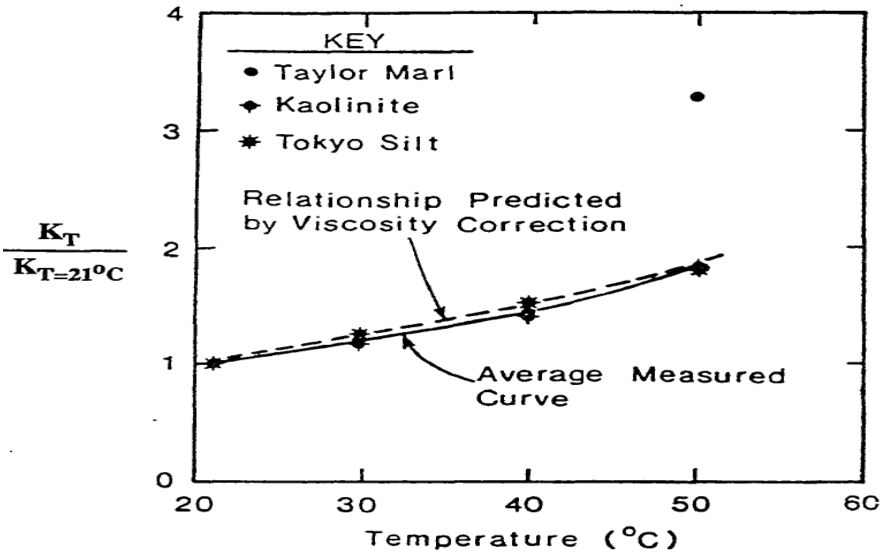


Figure 2.7: The effect of temperature on the hydraulic conductivity of fine-soils, Taylor marl, kaolinite, and Tokyo silt (after Olson and Daniel, 1979).

2.5.3 Assessment of the hydraulic conductivity of soils

One of the most difficult tasks encountered by geotechnical engineers is how to obtain an accurate and reliable value for the hydraulic conductivity (k_h) of soils, particularly fine-grained soils of low permeability. The possible approaches include; measuring k_h directly in the field, measurement k_h directly/indirectly in the laboratory on natural or reconstituted samples, prediction of k_h using known formula which were produced from experimental data. In what follows, a brief presentation of the common methods for determining the coefficient of hydraulic conductivity of soils is given.

2.5.3.1 Laboratory methods and permeameter types

The coefficient of hydraulic conductivity is best measured directly either in laboratory or in field. Laboratory tests under controlled conditions are always required to understanding the behaviour and modes under different range of stresses, densities, saturations. Also, laboratory methods are more suitable in terms of cost, time, and simplicity. Nevertheless, data obtained from the actual field measurements are more relevant in design because they include the effect of soil fabric.

- ***Laboratory methods***

A number of test methods are commonly used for measuring hydraulic conductivity in laboratory. These methods include constant head, falling head, and constant flow. All the methods use steady-state conditions and assume Darcy’s law is valid. For each of these test methods, there are advantages and disadvantages in use, simplicity, cost, time needed for test completion. A brief overview of these testing laboratory methods is given below.

(1). Constant head test - This test is described in more detail in standards (BS 1377-5: 1990, ASTM D2434-68 and D5084-16). It has been successfully adopted to determine the hydraulic conductivity of coarse-grained soils (e.g. gravels and sands) and fine grained soils of low plasticity (e.g. silts) (see e.g. Tavenas et al., 1983b, Araruna et al., 1995, Chen, 1997). The typical arrangement of the constant head test is shown in Figure 2.8a. A known constant hydraulic gradient (i) is imposed across a soil sample of a known cross sectional area (A) and length (L), and the resulting flow rate (q) is measured. Using Darcy's law, the hydraulic conductivity (k_h) is known from:

$$k_h = \frac{q.L}{A.h} \tag{2.8}$$

A limitation in the constant head test is the complexity of measuring a relatively small rate of flow. This can be possibly tackled by either extending the test time or applying a very high hydraulic gradient so to produce a reasonable measurable flow. The value of the hydraulic gradient imposed should be similar and compatible with that occurs in the field. An excessive gradient should not be used to avoid seepage-induced consolidation that causes the permeability of the soils to be reduced. The recommended values of the maximum hydraulic gradients are given in Table 2.2.

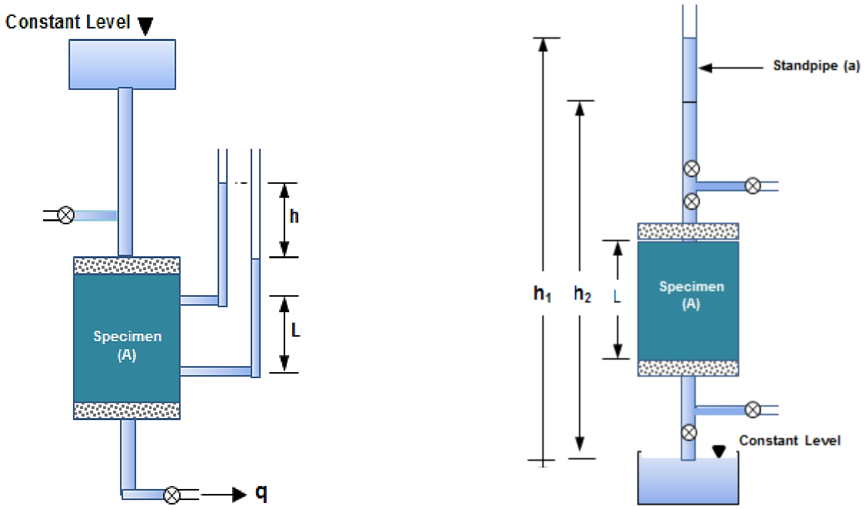
Table 2.2: The recommended hydraulic gradient in soils, as per ASTM D5084

Soil permeability (m/s)	Maximum hydraulic gradient
$10^{-5} - 10^{-6}$	2
$10^{-6} - 10^{-7}$	5
$10^{-7} - 10^{-8}$	10
$10^{-8} - 10^{-9}$	20
Less than 10^{-9}	30

(2). Falling head test - The falling head test is used for measuring the hydraulic conductivity of fine-grained soils of relatively low permeability (e.g. clays). A typical set up for the test is presented in Figure 2.8b. A small diameter stand-pipe (a) is connected to the inflow of a sample of known cross-sectional area (A) and length (L), and the outflow head is kept constant during the test. The permeant level in the stand pipe at the start (h_1) and end (h_2) of the test is measured during a specific duration ($t_2 - t_1$) and the hydraulic conductivity (k_h) is determined from:

$$k_h = \frac{a.L}{A.(t_2 - t_1)}.ln\frac{h_1}{h_2} \tag{2.9}$$

The test equipment of the falling head test is simpler than that used in the constant head test. However, it has significant limitations that were recognized by some scientists (Daniel, 1994, Pane et al., 1983, Tavenas et al., 1983b). The drop in head difference applied to a sample during the test results in a reduction in pore pressure and at a very low effective stresses, the air bubbles held by the pore water can be released influencing the hydraulic conductivity. Pane et al. (1983) and Tavenas et al. (1983b) stated that the unavoidable change of the head difference makes it very difficult for the steady state condition of Darcy's law to be achieved. This is due to the fact that the hydraulic potential is continuously changed during the falling head test. A falling head test generally takes a long time because of the low permeability of the soil. Increasing the potential difference can accelerate the test, but seepage-induced consolidation can occur which may affect the measured hydraulic conductivity.



(a) (b)

Figure 2.8: Typical arrangement of (a) constant head test, (b) falling head test

(3). Constant flow test - The constant flow test has been used as a modern method for testing fine-grained soils of low and intermediate hydraulic conductivity (e.g. fine sands, silts, and clays). This test has been proposed as a standard method in the ASTM D5084 -16. The test is carried out by inducing a known flow rate of permeant through a soil sample using a multispeed pump device and the resulting pressure difference across the sample is measured using a differential pressure transducer (DPT) as shown in Figure 2.9. This type of test was first used by Olsen (1966) and the results obtained were quite satisfactory. While this technique has been shown some advantages in measuring the hydraulic conductivity of fine soils, the cost required to set up and build this technique is still quite high and also the operation of the system is somewhat complicated.

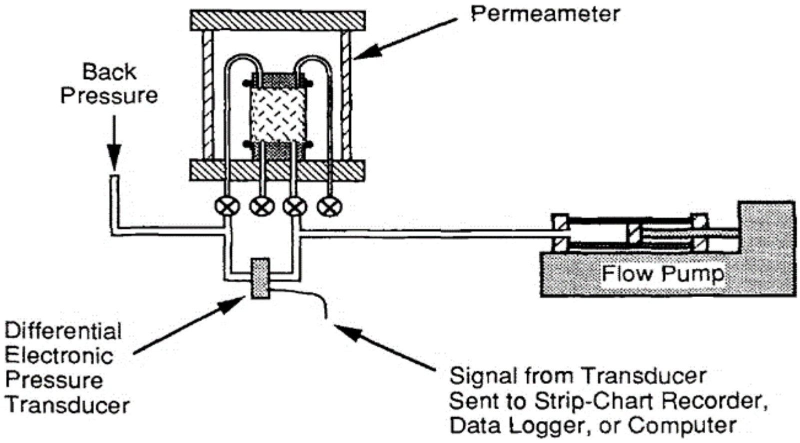


Figure 2.9: Typical arrangement of constant flow test (after Daniel, 1994).

(4). Consolidation test - The hydraulic conductivity can be determined indirectly from a one-dimensional consolidation test on fully saturated soil samples based on the assumption of Terzaghi’s theory. In the present research, the coefficient of hydraulic conductivity was first determined indirectly from a series of consolidation tests on a wide range of composite soils.

- ***Permeameters types***

Two types of permeameters can be used to measure the hydraulic conductivity; rigid wall and flexible wall permeameters. The essential difference between them is in the process of consolidation in that one-dimensional consolidation is performed in the rigid-wall permeameter whereas three-dimensional consolidation process is used in the case of the flexible-wall permeameter. A brief overview of these two types is provided below:

(1). Rigid wall permeameter - The rigid-wall permeameter consists of a rigid tube that hold a soil sample inside and the tube is made of metal, plastic, or even glass. Two types of rigid wall permeameter are used in the measurement of hydraulic conductivity of soils; compaction-mould permeameter and consolidation-cell permeameter.

The compaction-mould permeameter is the most common type (Figure 2.10a). The sample is directly compacted and confined in the rigid cylindrical mould. The main advantages of this type are; simplicity in test, low cost, very suited to test compacted samples, and no need for high stresses. However, one of its disadvantages is the difficulty to fully saturate the sample as most of compaction moulds do not have a means to apply a back pressure. Also, it is very difficult to measure the rate of swelling and shrinkage using this type of permeameter and the stresses applied to the sample are uncontrolled. The compaction-mould permeameter is more utilized in the measurement of the permeability of fills and liners that have similar features in situ in that the applied stresses are relatively low.

The consolidation-cell permeameter is a modified consolidation cell, such as the one shown in Figure 2.10b, which can be adapted to measure the hydraulic conductivity. In this permeameter, a wide range of stresses compatible to those in the field can be applied to a fully saturated sample. This kind of test is best used for testing undisturbed and reconstituted samples that are subject to high levels of stress in the field (e.g. composite soils of high to moderate compressibility characteristics).

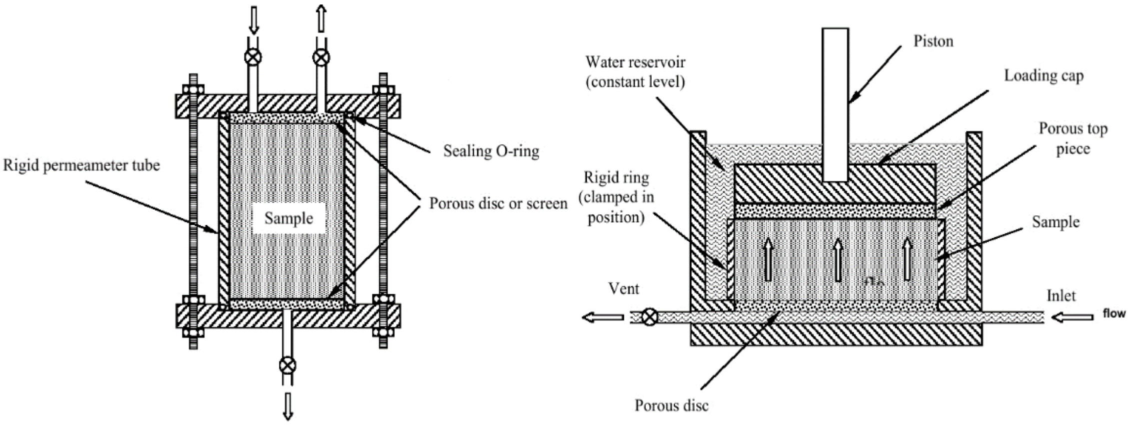


Figure 2.10: Schematic of rigid wall permeameters; (a) compaction-mould, (b) consolidation-cell (from Hudson, 2007).

(2). Flexible wall permeameter - Of all flexible wall permeameters, the triaxial cell is the most widely accepted and used in the measurement of the hydraulic conductivity of soils (Figure 2.11). The cell components and the test procedures are described in the standards (BS 1377-6: 1990 and ASTM D5084-16). There are a number of advantages associated with the triaxial flexible cell including the ability to saturate the sample with the aid of back pressure system under controlled condition of stress (vertical and horizontal stresses), undisturbed natural samples with irregular surfaces can be tested, and its suitability to use with chemical fluids other than distilled water. The only limitation of the cell could be in the cost of the whole system used for the testing.

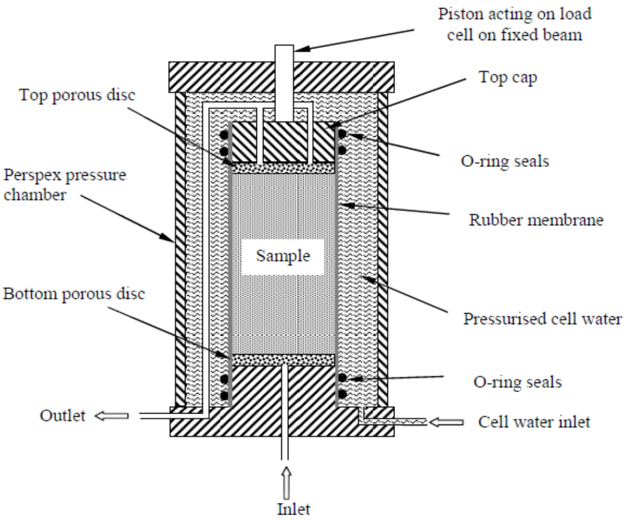


Figure 2.11: Schematic of flexible wall permeameters (triaxial cell) (from Hudson, 2007)

2.5.3.2 Field measurements

Field applications test a more representative volume of soil. However, most in situ tests are expensive and time-consuming. The complexity of controlling the sample conditions (i.e. level of saturation, depth of test area, sample volume for testing) is another major limitation. In the literature, there is no unique standard test and most of the available methods have different assumptions leading to different results.

Field methods for testing hydraulic conductivity include; boreholes, porous probes, infiltrometers, and underdrain testing methods. Detailed and more extensive discussions of the field hydraulic conductivity testing methods are provided by Daniel (1989) and Ragab et al. (1990). The present study is only limited to the laboratory testing methods of hydraulic conductivity of soils.

2.5.4 Prediction of the hydraulic conductivity of soils

As described in section 2.5.3, the majority of the laboratory and in situ measurements of the hydraulic conductivity are quite expensive and time-consuming (especially field testing systems). Further, they are very likely to include uncertainties associated with applicability, reliability and interpretation of the data obtained. For any test region, the variation of the hydraulic conductivity in both space and time is quite considerable making it difficult to obtain a representative value.

A number of researchers have addressed how to derive the coefficient of hydraulic conductivity from the other soil's properties. These hydraulic predictive models have either theoretical, empirical or semi-empirical basis relating the k_h with the physical properties of soils (e.g. Atterberg limits, void ratio, particle size distribution). A summary of the more commonly used predictive models is presented in Table 2.3.

Table 2.3: Predictive methods of hydraulic conductivity (modified from Chapuis, 2012)

no	Author(s)	Year	Dependency of the predictive method			
			Type of soil	*PSD*	n or e_g	I_L, I_P, or P_I
1	Seelheim	1880	any soil	Yes	No	
2	Hazen	1892	Sand, gravel	Yes	$e=e_{max}$	
3	Slichter	1898	Spheres	No	Yes	
4	Terzaghi	1925	Sand	Yes	Yes	
5	Mavis and Wilsey	1936	Sand	Yes	Yes	
6	Tickell and Hiatt	1938	Sand	Yes	yes	
7	Krumbein and Monk	1942	Sand	Yes	No	
8	Craeger et al. N1	1947	Sand, gravel	Yes	No	
9	Taylor	1948	Sand, clay	No	Yes	
10	Loudon	1952	Any soil	No	Yes	
11	Kozeny	1953	Sand	Yes	Yes	
12	Wyllie and Gardner	1958a,b	Any soil	No	Yes	
13	Harleman	1963	Sand	Yes	No	
14	Beyer	1964	Sand	Yes	No	
15	Masch and Denny	1966	Sand	Yes	No	
16	Nishida and Nakagawa	1969	Clay	No	Yes	Yes
17	Wiebenga et al.	1970	Sand, silt	Yes	No	
18	Mesri and Olson N2	1971	Clay	No	Yes	
19	Beard and Weyl	1973	Sand	Yes	Yes	
20	Navfac DM7	1974	Sand, gravel	Yes	Yes	
21	Samarasinghe et al.	1982	Clay	No	Yes	Yes
22	Carrier and Beckman	1984	Clay	No	Yes	Yes
23	Summers and Weber	1984	Any soil	Yes	No	
24	Kenney et al.	1984	Sand	Yes	Yes	
25	Shahabi et al.	1984	Sand	Yes	Yes	
26	Kaubisch and Fischer	1985	Any soil	Yes	No	
27	Driscoll N3	1986	Gravel, sand	Yes	Yes	
28	Shepherd	1989	Sand, silt	Yes	No	
29	Uma et al.	1989	Sand	Yes	No	
30	Nagaraj et al.	1991	Clay	No	Yes	Yes
31	Vukovic and Soro N5	1992	Sand	Yes	Yes	
32	Kenney et al.	1992	Compacted sand-clay	No	No	No (k_B)
33	Alyamani and Sen	1993	Mostly sand	Yes	No	
34	Sperry and Pierce	1995	Granular	Yes	No	
35	Boadu	2000	Any soil	No	Yes	
36	Sivappulaiah et al.	2000	Clay-Sand	No	Yes	Yes
37	Mbonimpa et al.	2002	Any soil	Yes	Yes	Yes
38	Chapuis and Aubertin	2003	Any soil	Specific surface	Yes	No
39	Chapuis	2004b	Natural soils	Yes	Yes	
40	Berilgen et al.	2006	Clay	No	Yes	Yes
41	Chapuis et al.	2006	Compacted clay	Yes	Yes	
42	Ross et al.	2007	Any	No	Yes	
43	Mesri and Aljouni	2007	Peat	No	Yes	
44	Dolinar	2009	Clay	No	Yes	Yes
45	Sezer et al.	2009	Granular soil	No	Yes	
46	Arya et al. N6	2010	Golf sand	Yes	Yes	
47	Tripathi	2013	Bentonite, sand-bentonite	No	Yes	No

Ragab et al. (1990) and Chapuis (2012) provided an extensive review of a range of such hydraulic models and reported that many of them are flawed because of errors in the experimental procedures. Chapuis (2012) reached a conclusion that the methods produced by Hazen (1892) coupled with Taylor (1948), and Chapuis (2004b) provided a reliable estimate for coarse grained soils based on:-

$$k_h = A\,\frac{{e_g}^3}{1+e_g} \tag{2.10}$$

Where A is a constant depends on the particle size distribution and e_g is the global void ratio.

For fine-grained soils, Chapuis (2012) found that the regional relationship would provide a reasonable prediction for k_h:-

$$log_{10}\,k_h = a + b\;log_{10}\left[\frac{{e_g}^3}{1+e_g}\frac{1}{I_L^2}\right] \tag{2.11}$$

Where I_L is the liquid limit. The two equations (2.10 & 2.11) suggest that for composite sand-clay soils, k_h should be a function of the void ratio, particle size and Atterberg limits. In clast dominated (or coarse) composite soils, the flow could be dependent on the intergranular void ratio whereas in matrix (fine) dominated composite soils, it could be a function of the matrix void ratio. In this study on composite soils, an investigation was undertaken to determine whether there is a relationship between the hydraulic conductivity of composite soils and these parameters.

2.6 Flow of heat through soils

Heat can be defined as the work required to move a specific amount of energy through a conducting body by a virtual potential (Boles, 2014). In soils, heat is transferred mainly by three different mechanisms; conduction, convection and radiation. Soils consist of solid particles that are surrounded by pores (filled by either air or water or both). The thermal conductivity of all types of solid particles is much higher than the water or air phases. Therefore, the preferred path for heat to transfer through soils is essentially in the solid particles, and then water and air.

While all of conduction, convection and radiation mechanisms are collectively participated in the transfer of heat through soil's constituents (Figure 2.12), the most dominant mechanism of heat transfer through most soils is conduction. Thus, thermal conductivity is considered the most important property in most soils to govern the heat transfer (Mitchell and Soga, 2005).

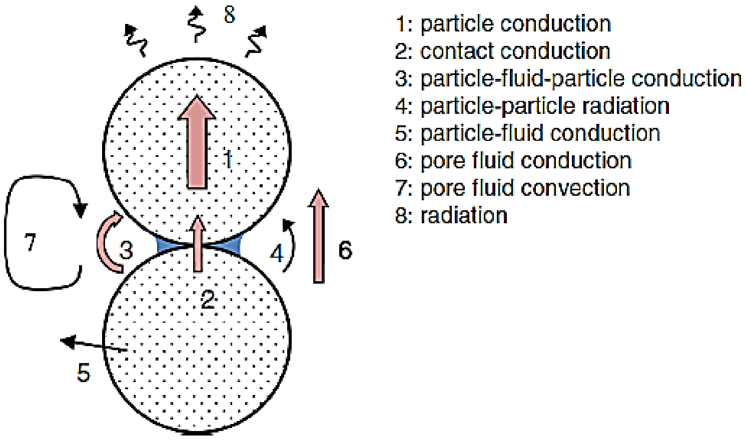


Figure 2.12: The mechanisms of heat transfer through soils (adapted from Dong and Pamukcu, 2015).

Whenever there is a temperature difference in a soil, heat begins to travel from the regions of high temperature to those of low temperature. The rate at which the heat flow is directly proportional to the temperature difference, or gradient. This phenomena was discovered further by Fourier (1822) who introduced a very valuable contribution to the world of heat transferring by conduction, an empirical law based on actual observations (called it Fourier's law). He suggested that the rate of heat flow through porous materials and solids of known area is directly proportional to the area of the section at right angles to the direction of heat flow (Figure 2.14), and to the temperature gradient in the direction of the heat flow.

$$q = k_t \frac{\Delta T}{L} A = k_t \frac{T_1 - T_2}{L} A \qquad (2.12)$$

Where q = the rate of heat transfer (W).

k_t = the coefficient of thermal conductivity (W/m °C).

A = cross-sectional area of the conducting body (m^2).

L = the specific length between two points of different temperatures (T_2) and (T_1).

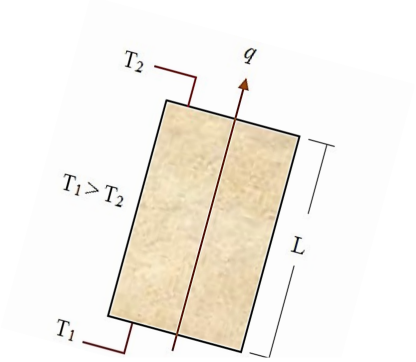


Figure 2.13: Principle of heat transfer in materials

Heat can be transferred by the mechanism of convection in and from the materials (e.g. soils) by natural or forced nature of flow. In natural convection, the heat mainly flows because of the migration of air or/and water molecules in the soil which result from the difference in density caused by the temperature change. This kind of convection occurs mostly in nearly dry coarse-grained soils. Forced convection is produced by any type of external means; i.e. by fan (wind) or pump (hydraulic gradient). It is significant in soils of high permeability (e.g. in coarse-grained soils). Groundwater flow is one of the example of this type in field. Flowing water through a soil as a result of a hydraulic gradient has an important role on the magnitude of the effective thermal conductivity of the soil. According to Farouki (1981), convection of heat by fluid in coarse soils (e.g. in coarse sands) can sometimes cause a substantial increase, up to 20%, in the value of the effective thermal conductivity of the soils.

Through the mechanism of conduction and convection, the internal energy (or heat) is transferred within a body, this energy, however, may also be transferred through pore spaces due to the motion of electromagnetic wave produced by the temperature of the radiating body to be absorbed by other objects. This type of process is called radiation. Thermodynamic observations indicate that the ideal radiator has the ability to release energy at a rate proportional to the fourth power of the entire temperature of the object and directly proportional to the surface area (Kustas and Daughtry, 1990). However, in most soils, the contribution of the radiation to heat transfer is not very significant, less than 2% (Rees et al., 2000), and when the particle size is larger than 20mm, the effect can rise to ten percent of total heat transfer (Farouki, 1986). Hence, heat transfer by radiation is only significant for dry coarse gravel.

2.6.1 Thermal conductivity of soils

As stated in section 2.6, the coefficient of thermal conductivity in soils is the most effective thermal parameter controlling the rate at which the heat transfers through the soils, particularly in fine-grained soils of low permeability. Unlike hydraulic conductivity, the range of difference in the value of the thermal conductivity from coarse to fine soils is small (see Table 2.7). Nevertheless, it varies within one/two orders of magnitude ranging from (0.25 – 4.5 W/m ^{o}C) depending on a soil's composition and physical properties.

2.6.2 Factors influencing thermal conductivity of soils

The thermal conductivity of soils is not a constant parameter but depends largely on the soil's properties. As a soil consists of solid particles surrounded by pores of different sizes and shapes that are filled with air or water or both, the range of variation in their thermal conductivity characteristics makes the interpretation of heat transfer through the soil much more complicated than that for rigid homogeneous body that has stable, well-known thermal properties (e.g. thermal conductivity and heat capacity). The factors influencing thermal conductivity of soils can be grouped into two main categories: compositional and environmental factors. In what follows, some of these common factors are presented.

2.6.2.1 Compositional factors

The compositional factors include particle size distribution and mineralogical composition of soil's constituents. The role of these two parameters are essential on controlling and determining the thermal conductivity of soils.

The particle size, and more importantly the particle size distribution, has a very strong connection with the soil porosity, mineralogy, surface area, and permeability. The effect of particle size on the heat transfer in soils has been investigated by a number of researchers (e.g. Rzhevskii et al., 1971, Brigaud et al., 1990, Beziat et al., 1992, Griffiths et al., 1992, Jones and Pascal, 1994, McKenna et al., 1996, Tavman, 1996, Midttomme and Roaldset, 1998, Hamuda, 2009). They found a direct relationship between the effective thermal conductivity and particle size attributing that to the fact that as the grain size increases, the solids per volume unit will be less to reach a certain porosity/density meaning that the resistance between particles is less. The particle size also governs the number of particle contacts that constitute one of the key paths for heat to transfer though soils, more strongly in dry or nearly dry soils and partially-saturated soils of low water content (Smith, 1942, Tarnawski et al., 2002).

The coefficient of thermal conductivity is highly dependent on the thermal conductivities of soil’s constituents (solid particles, water, and air) and their respective volume fractions. The mineral composition of the solid particles is often unknown without a clear and detailed mineralogical analysis. Typically, a soil can contain particles of more than one type of minerals. These minerals can be grouped into two categories; non-clay minerals (e.g. quartz, calcite, …etc) and clay-minerals (e.g. kaolinite, bentonite, sepiolite and attapulgite). While the thermal conductivity of non-clay minerals can be obtained indirectly from investigations on samples of parent rocks according to Côté and Konrad (2007), there is a lack of information and knowledge on the thermal conductivity of the clay minerals. The complicated processes of the fine-deposit formations make it difficult to obtain high quality parent samples. The limited data on the compositional mineralogy and saturation condition makes most of the published works on thermal conductivity of clays, in general, undependable. Therefore, in this research, soils of known composition (known sand, clay and water amount) were used in the measurements of the thermal conductivity in an attempt to establish some relationships between a soil’s composition and its thermal conductivity and to determine the thermal conductivity of sand- and clay- minerals indirectly.

2.6.2.2 Environmental factors

Water content, density, porosity, and temperature are the most critical environmental factors that affect the thermal conductivity of soils.

A series of studies on the variation of water content with the thermal conductivity of partially saturated soils has been explored (e.g. Farouki, 1986, Singh and Devid, 2000, Nusier and Abu-Hamdeh, 2003, Côté and Konrad, 2005b, Sakaguchi et al., 2007). They collectively concluded that when the water content increases, the thermal conductivity of the soils increases with all other properties being constant.

For partially saturated soils of very low water content, most pore spaces are filled with air having an extremely low thermal conductivity (k_t = 0.025 W/m °C). The water is either adsorbed on the external surfaces of the particles, particularly clay particles, or available freely within the pores between the particles, i.e. in sand particles. At this stage, the heat transfers mostly through particles and at their contacts. Addition of water enhances the heat flow by creating bridges around the particle contacts. As the water content increases, the water begins to replace the air in the pores and, because the thermal conductivity of water (k_t = 0.57 W/m °C) is much higher than air, the overall soil thermal conductivity increases. The rate of increase in the thermal conductivity will be significant in the first instance when the water content increases, but beyond a specific water content, this increase becomes much smaller (Singh and Devid, 2000). An example of the relationship between the thermal conductivity and water content in partially saturated soils is presented in Figure 2.14.

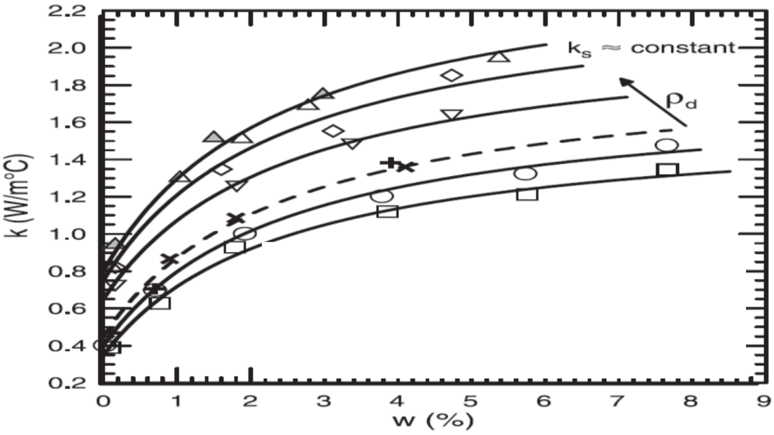


Figure 2.14: The relationship between thermal conductivity (k_t) and water content (w_c) at different densities (p_d) (from Côté and Konrad, 2005b)

The above argument agrees well with soils of three-phases (i.e partially saturated soils). However, for fully-saturated soils, the relationship between water content and thermal conductivity may have a different trend. In fully saturated states, when the water content is reduced by any external means (i.e. under consolidation processes), some of water in pores leave the soil, and is then replaced by the higher thermal conductivity solids. The solids per volume in soil become greater leading to an increase in the thermal conductivity. In fact, under applied loads, any change in water content is associated with a change in the soil density which means that the density and water content are the most significant physical parameters that affect the thermal conductivity in fully saturated soils.

A number of researchers have reported that when a soil density increases, or the porosity decreases, the thermal conductivity increases (Smith, 1942, Kersten, 1949, Becker et al., 1992, Abu-Hamdeh and Reeder, 2000, Abu-Hamdeh, 2003).The probable explanation of this is that increasing density implies that the low thermal phase (water in saturated soil, or air in dry or partially saturated soils) is replaced by the higher thermal conductivity phase (solid particles). Solid particles per unit volume are closely packed and the number of contact points increases providing an additional means for heat to transfer. An example of k_t and particle contacts with dry density is shown in Figure 2.15.

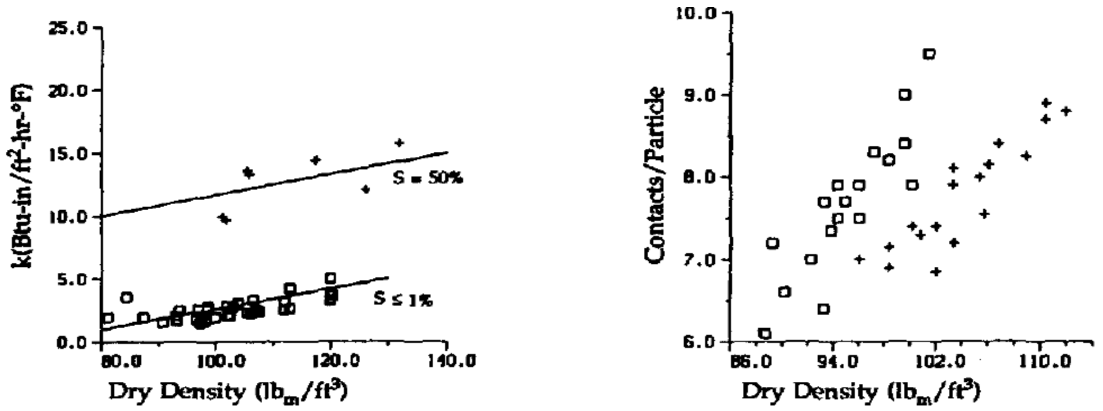


Figure 2.15: The effect of dry density on particle contacts and on the thermal conductivity (taken from Becker et al., 1992).

The overall thermal conductivity of soils can also be influenced by the variation of temperature. An increase in temperature has a different impact on each of soil's constituents. Brandon and Mitchell (1989) found that most of soil crystallised minerals exhibit a reduction in their thermal conductivity when the temperature is increased. van Rooyen and Winterkorn (1957) reported that as the temperature increases, the thermal conductivity of water and air increases. A series of studies have been conducted on assessing the effect of temperature on the overall soil conductivity (e.g. Sepaskhah and Boersma, 1979, Campbell et al., 1991, Hamuda, 2009). The results showed that increasing the temperature causes an increase in the thermal conductivity and the rate of this increase is mainly associated with the water content of the soil. The influence is more noticeable in nearly dry soils. However, in saturated soils, Hamuda (2009) showed that increasing the temperature from 25.49 °C to 38.92 °C resulted in a very slight increase (nearly 1.6%).

2.6.3 Assessment of the thermal conductivity of soils

Three possible approaches can be used in the assessment of the thermal conductivity (k_t) of soils. The first approach is to measure k_t directly in the field. The second approach is to measure k_t in the laboratory on compacted or consolidated samples (either undisturbed samples collected from the field or reconstituted samples). The last approach is to use predictive models that are based on the physical properties of the soils. A brief review of these approaches is presented below.

2.6.3.1 Field and laboratory thermal measurements

While tests on actual soil depositions provide the actual thermal conductivity values, laboratory measurements under controlled boundary conditions are often necessary to gain a better understanding of the thermal behaviour under a range of stress, density, water content, degree of saturation, and other compositional parameters. Generally, two methods are used in the laboratory measurements of the thermal conductivity; steady-state and transient methods. They differ in assumptions, testing equipment and procedures, and the duration of the test. In general, laboratory tests of the thermal conductivity are carried out either by measuring the power required for generating a constant temperature difference, or by applying a constant power and the resulting temperature variations in the sample are measured. A brief overview of the methods used in the thermal conductivity measurements is presented below.

(1). Steady-state methods - Once a potential of temperature difference is generated across a soil sample, the measurements are taken after the steady-state condition is reached, which takes some time. Different methods using the steady-state principles are found but the two most commonly used methods are; the guarded hot plate (GHP) and the radial heat flow (RHF). These methods are classified according to the heat flow direction and both are assumed to obey Fourier's law of heat conduction. A brief discussion of these two steady-state methods is given below:

- **The guarded hot plate (GHP) -** Of all steady-state methods, the guarded hot plate (GHP) is the most important and widely used for measuring the thermal conductivity parameter of materials, particularly those of low conductive properties. Since 1963, this method has been standardized by the ASTM to be to measure thermal conductivity. The standard covers only the general requirements of test design and does not provide further details about the equipment specifications. Hence, the success of the testing method depends largely on the proper design and efficiency of the equipment.

The general specification of the GHP equipment that is covered by the ASTM is shown in Figure 2.16. It consists of guard plates of 20 inches that have the ability of measuring temperatures in range of -50 to +250. Two identical samples are held between thin plates containing a heater element, and surrounded by external guard heater reducing the horizontal heat losses and ensuring heat flows vertically. Sink plates with cooled water are placed near to the outer edges of the samples and the measurement are taken.

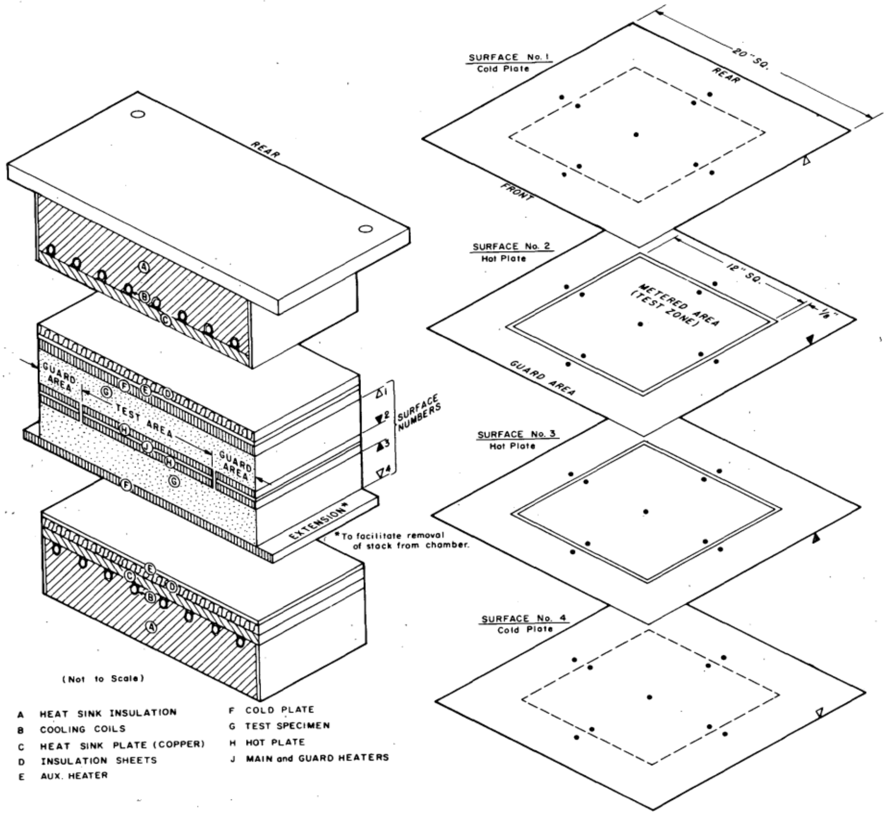


Figure 2.16: The basic arrangement of the guarded hot plate (GHP)

Although studies using the GHP method have shown that the results vary within 20% for a certain material, the results are considered reliable (Farouki, 1986). However, the test needs too long a time to achieve the steady-state conditions and in some instances, unavoidable water migration occurs especially in unsaturated soils.

- **Radial Heat Flow (RHF) -** While the guarded hot plate (GHP) used flat rectangular samples, it is possible to use cylindrical shapes with the steady-state radial heat methods (RHF). RHF is more suited for testing powdered and granular materials. The schematic details of the RHF equipment is presented in Figure 2.17. After inserting the sample in the mould of the equipment, a known power is applied and the temperature variations in sensors pushed inside the sample are measured and recorded. Using the application for Fourier's law, the thermal conductivity is determined.

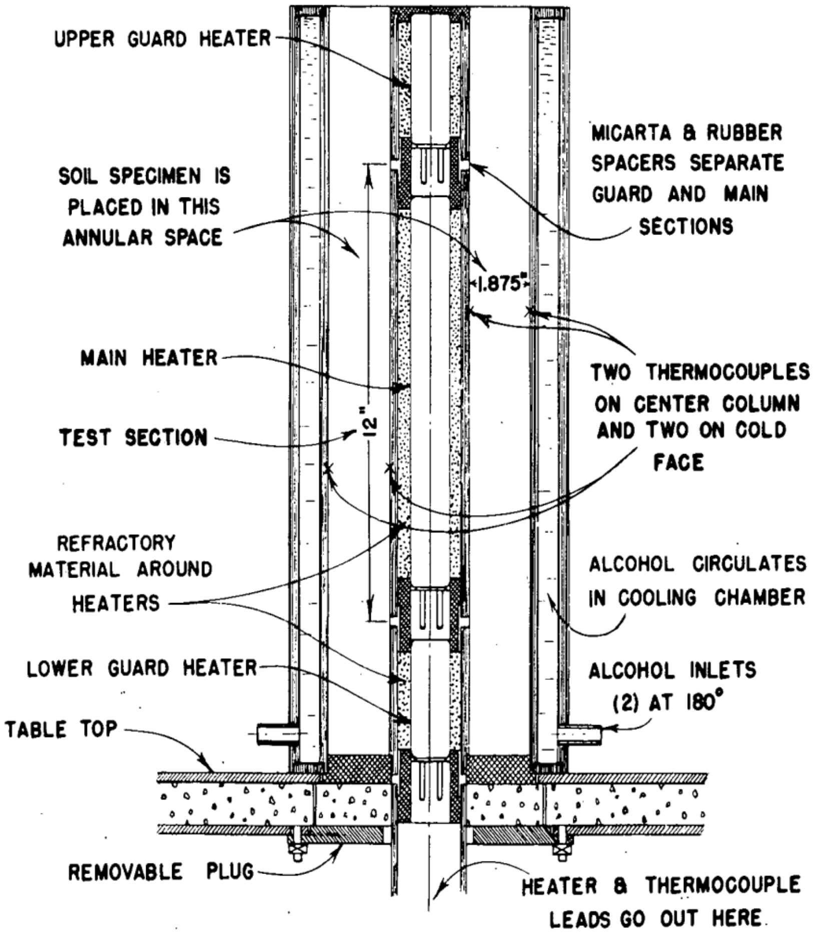


Figure 2.17: The schematic details of RHF based equipment (from Farouki, 1981)

Various scientists have used this method for measuring the thermal conductivity of soils (e.g. Kersten, 1949, Mitchell and Kao, 1978).

(2). Transient-state methods - The major limitation of the steady-state methods is the long-time involved in the measurements. The transient methods are faster and easier in the measurements, and therefore, they can be more versatile in use. The transient methods have also a potential capability of measuring the thermal diffusivity directly, but the accuracy is not very high as in the steady-state methods (Mohsenin, 1980).

The theory of line heat source is the basis of all transient thermal methods. They assume that the heat dissipation in soils can be equivalent to that of heat conduction. The hot wire, the thermal needle probe (single probe), and the dual probes are the most common transient methods. These three methods are presented briefly.

- **Hot wire method -** The transient hot wire method has been standardized and covered by the American Society for Testing and Materials as ASTM C 1113. The simplicity in setup and measurements involved in the thermal test increases its use. A thin, straight wire acting as the heat source is pushed into the centre of a soil sample held by a metal container. When the temperature is constant, power is supplied to the wire to heat up the sample, and the temperature variations are measured by a built-in thermocouple. The thermal conductivity is determined from the rise in temperature within two known times and the supplied power as:

$$k_t = \frac{Q}{4\pi\ (T_2 - T_2)} . ln\left(\frac{t_2}{t_1}\right) \qquad (2.13)$$

Where Q is the supplied power per unit length, T_1 and T_2 are the temperatures at time t_1 and t_2, respectively.

Abu-Hamdeh et al. (2001) used the arrangement in Figure 2.18 to assess the influence of water content and dry density on the effective thermal conductivity of some soils. They showed that the hot wire method can effectively be used to measure the thermal conductivity. However, the method needs a very good contact between the embedded wire and the surrounding soil. Therefore, it is mostly used for cohesive soils.

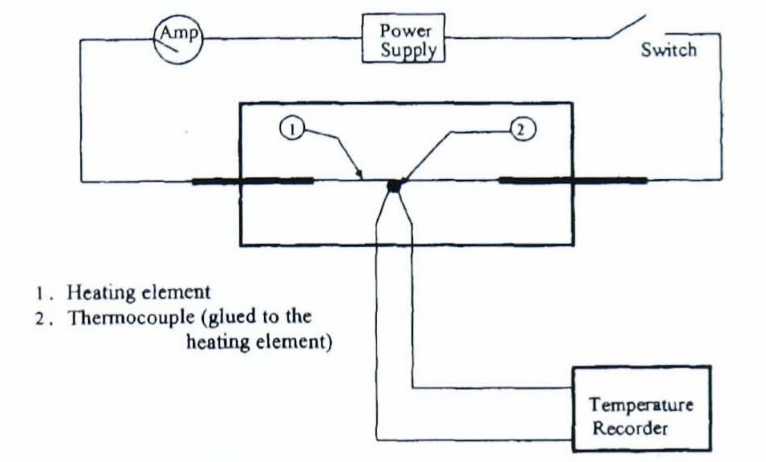


Figure 2.18: Simple diagram of hot wire method (after Abu-Hamdeh et al., 2001)

- **Needle Probe Method (Single Probe) -** Similar to the hot wire method, the needle probe method also depends on the line heat source theory. This method requires two essential components; a single probe made of metal containing a heater element, and an external or built in thermocouples. The use of the thermal needle probe method was due to Hooper and Lepper in 1950 to measure the thermal conductivity of soils depending on a single large probe (47 cm in length, 0.47 cm in diameter). The set up and measurement by the needle probe method are very similar to that used in the hot wire method, expect that the needle is used instead of the straight wire generating a temperature difference in the sample. A complete description of the components, arrangement and procedures is described further in the ASTM D5334-14. The standard states that this method is applicable for isotropic materials with temperature between 20 to 100 °C.

The simplicity and rapidity of the single needle method has been recognised by a number of researchers (e.g. Chaney et al., 1983; Nusier and Abu-Hamdeh, 2003). In this method, it is possible to determine the thermal resistivity directly from the data without a need for the heat capacity of the soil (Mitchell et al, 1978). Despite these advantages, the thermal needle probe still has an issue associated with the assumption of specific heat that usually leads to an error in the interpretation. Also, any variation, even if it is very small, in the supplied power during the test can provide inaccurate readings (Mitchell et al., 1978). This is why there should always be a need for calibrating the probe before testing.

- **Dual probe method -** Two thermal probes at a known distance apart are used in this method. An instrument using the dual probe principles was developed by Campbell et al. (1991). This instrument permits measurements of the volumetric heat capacity of soils and both the thermal conductivity and diffusivity are extracted using the heat-pulse theory suggested by Bristow (1998). Thus, it can be used effectively with other soil properties for determining the volumetric water content.

2.6.4 Prediction of the thermal conductivity of soils

Thermal conductivity of soils can generally be known from direct and indirect assessments. When no thermal data or direct measurements exist, the thermal conductivity can be estimated indirectly from the soil's properties (e.g. mineralogical composition, porosity, water content, dry density).

Several thermal conduction models for predicting thermal conductivity of soils have been developed and are available in the literature. These models vary in simplicity, applicability and some of them may even be limited to a specific type of soils. The majority of the predictive models used predict the thermal conductivity from the soil's constituents and their respective volume fractions (e.g. Mickley, 1951, De Vries, 1952, Johansen, 1975). Other models were empirically produced by curve-fitting of data available (e.g. Kersten, 1949). A summary of the most common thermal models is given in Table 2.4. While the parallel and series flow models define the upper and lower limits for all thermal models, any model in Table 2.4 should provide results lying between these two-limits (Farouki, 1982). It should be stated that the solid particles (or minerals) in these models are assumed to be assembled together with free inter-contacts and the water is in continuous state.

A validation assessment was conducted by Farouki (1982) on most of the thermal models who reached the conclusion that the model of Johansen (1975) gives the best results for estimating the bulk thermal conductivity of fine and coarse soils, which is in the form of:-

$$k_t = \left(k_{sat} - k_{dry}\right) * K_e + k_{dry} \qquad (2.14)$$

For fully saturated unfrozen soils, Johansen's formula can be reduced to:

$$k_t = k_{sat} = k_w^{x_w} k_s^{x_s} \qquad (2.15)$$

Where k_t is the bulk thermal conductivity (W/m °C), k_w, k_s are the thermal conductivity of water and solid particles, respectively (W/m °C), x_w, x_s are the volume fractions of water and solid particles in the soil matrix. Johansen (1975) assumed using the geometrical mean method for estimating the thermal conductivity of fully saturated soils because he showed that changes in soil's microstructure have a very small influence on the thermal conductivity. The applicability of the generalized Johnsen's model (equ. 2.14) has been then tested by several researchers on a wide range of thermal conductivity data (e.g. Sass et al., 1971, Brigaud and Vasseur, 1989, Midttomme and Roaldset, 1998, Côté and Konrad, 2005a, Côté and Konrad, 2005b, Côté and Konrad, 2007). This model was proven to provide an accurate estimate of the bulk thermal conductivity (k_t) of fluid-saturated soils provided that the correct and the more representative values are used for the thermal conductivity of the soil's minerals (k_s).

The thermal conductivity of non-clay minerals can be obtained from investigation on samples of parent rocks (Côté and Konrad, 2007) though it must be noted that the thermal conductivity of the parent rock will be different from that of a soil formed of particles of the parent rock because of contact thermal resistance between particles. However, there is a lack of information on the thermal conductivity of a wide range of common clay minerals (e.g. kaolinite, bentonite, sepiolite and attapulgite). This is due to the difficulty in obtaining high quality parent samples because of the complicated processes of fine-deposit formation. Further, the limited data on the compositional mineralogy and saturation condition makes most of the published works on thermal conductivity of clays are, in general, undependable.

In the literature, the thermal conductivity of soil's minerals (k_s) can be based on a number of semi-empirical expressions (e.g. Gemant, 1952, Johansen, 1975). One of the first formula to predict the solid thermal conductivity was due to Gemant (1952). Gemant correlated thermal conductivity of minerals (k_s) with the percentage of clay (Cm) in soil solid:-

$$k_s = a - bC_m \qquad (2.16)$$

Where a = 5.84, b = 3.3. Farouki (1982) reported some limitations in the use of Gemant's equation. On one hand, a value of 5.84 is obtained for quartz-dominated sands, which is considered too low in comparison with that of quartz,

k_s = 7.7 W/m°C. On the other hand, for clayey soils with no sand particles, the equation gives, k_s = 2.54 W/m°C, which, in turn, may be lower than those known values of clay minerals by about 25%. Therefore, using equ. (2.16) for estimating soil thermal conductivity of minerals is still open to question.

It is possible to calculate thermal conductivity of solids from the complete composition of a soil mineral content using the generalized geometric mean formula:

$$k_s = \prod_i k_{mi}^{xi} \tag{2.17}$$

where k_m is the thermal conductivity of an individual mineral i (W/m°C); and x is the volumetric fraction of the mineral i. Woodside and Messmer (1961) and Sass et al. (1971) used equ. (2.17) for estimating thermal conductivity of rocks. Equ. (2.17) is not always the best choice as the description of the mineral composition must be known which is, in practice, not often provided.

In an attempt to overcome this, Johansen (1975) developed equ. (2.17) further taking into account the thermal conductivity of only two constituents (quartz and other minerals) and their respective volume fractions as follow:

$$k_s = k_q^{x_q} k_o^{1-x_q} \tag{2.18}$$

Where k_q, k_o are the thermal conductivity of quartz and other minerals, respectively; x_q is the volume fraction of quartz in the soil-solid phase. Johansen assumed that the thermal conductivity of quartz equals to (k_q = 7.7 W/m°C), while the thermal conductivity of all other soil minerals equals to (k_o = 2 W/m°C in case of x_q > 0.2, and k_o = 3 W/m°C when x_q < 0.2). Côté and Konrad (2005b) suggested that equ. (3) provides good results for coarse soils of high quartz content, > 20%. However, they demonstrated that equ. (2.17) is much more suitable for estimating the thermal conductivity of soils with low quartz content (i.e. clays). It should be noted that the successful use of Johansen's equation (geometrical mean) is dependent on the knowledge of quartz content (x_q) in the soil solid phase. The quartz content is usually unknown and it is often taken as the sand content (x_s) (Peters-Lidard et al., 1998, Usowicz et al., 2006, Lu et al., 2007), which may be in some cases unreasonable. Another limitation in the use of Johansen's formula is that the quartz mineral itself could form a structure of unique arrangements that results in lower or higher thermal conductivity values. For instance, Clauser and

Huenges (1995) showed that the thermal conductivity of quartz ranges between 6.15 to10.17 W/m°C.

Table 2.4: Common thermal conductivity models of soils

Reference	**Formula**	**Definitions**	**Notes**
Parallel model	$k_t = k_w x_w + k_s x_s + k_a x_a$	k_t = Soil thermal conductivity $k_w,\ k_s, k_a$ = thermal conductivity of water, solid particles and air, respectively $x_w, x_{s,} x_a$ = the volumetric fractions of water, solid particles and air in the soil x_w = porosity (*n*) x_s = 1- *n*	- For saturated and partially saturated soils - Represents the upper limit of the thermal conductivity data
Series model	$\frac{1}{k_t} = \frac{x_w}{k_w} + \frac{x_s}{k_s} + \frac{x_a}{k_a}$	Similar to above	- For saturated and partially saturated soils - Represents the lower limit of the thermal conductivity data
Geometric mean model	$k_t = k_w^{x_w} * k_s^{x_s} * k_a^{x_a}$	Same as above	- For saturated and partially saturated soils - Represents the average of the thermal conductivity data
Kersten (1949)	$k_t = 0.1442\ [0.9\ log w_c - 0.2]\ 10^{0.6243 p_d}$	w_c = water content p_d = soil dry density	- For partially unfrozen silt-clay soils - Gives deviation of less than 25% of measured value of Healy clay, Fairbanks silty clay loam, Fairbanks silt loam, Northway silt loam and Ramsey sandy loam - Valid for w_c no less than 7%. - Not applicable for dry soils or crashed rocks.
	$k_t = [0.7\ log w_c + 0.4]\ 10^{0.01146 p_d}$		- For partially unfrozen sandy soils - Gives deviation of less than 25-31% of

Reference	Formula	Definitions	Notes
			measured value of Healy clay, Fairbanks silty clay loam, Fairbanks silt loam, Northway silt loam and Ramsey sandy loam. • This valid for w_c no less than 1%.
Mickley (1951)	$k_t = k_w a^2 + k_s(1-a)^2 + \frac{k_w k_s(2a-2a^2)}{k_w(1-a)+k_s a}$	*a* = air space of length $3a^2 - 2a^3 = n$	• For fully and partially saturated unfrozen soils • Don't apply for very porous and dry soils
De Vries (1952)	$k_t = \frac{k_w x_w + F k_s x_s}{x_w + F x_s}$	$F = \frac{1}{3}\sum_{a,b,c}\left[1 + \left(\frac{k_s}{k_w} - 1\right) g_a\right]^{-1}$ $g_a = g_b = 0.125\ and\ g_c = 0.75$	• For saturated soils, it gives good fit within 10% of the measured data • For dry soils, it gives lower values by 25% of the measured.
Van Rooyen and Winterkorn (1959)	$k_t = \frac{1}{A\ 10^{-BS} + s}$	*S* = degree of saturation *A, B,* and *s* = constants that are functions of soil density (ρ_d), the mineral type and geometry $A = 10^{a_1 - 0.44\rho_d^2}$, $B = b_1 - 5.5\rho_d,\ s = s_1 - s_2\rho_d$ a_1, b_1, s_1, and s_2 are functions of soil type and quartz content	• Developed empirically from data on crushed quartz, Ottawa sands and some natural soils
Maxwell (1954)	$k_t = k_w \frac{2x_w k_w + (3-2x_w)k_s}{(3-x_w)k_w + x_w k_w}$		• Theoretical model based on the electrical form of Maxwell • Not applicable for low porosity media
Kunii and Smith (1960)	$k_t = k_w\left[x_w + \frac{x_s}{\emptyset + (\frac{2k_w}{3k_s})}\right]$	$\emptyset = \emptyset_2 + (x_w - 0.259)\ (\emptyset_1 - \emptyset_2)/0.217$ $\emptyset_1 or\ \emptyset_2 = \frac{1}{2}\frac{[(k_r-1)/k_r]^2 sin^2\theta}{\log_e[k_r - (k_r-1)cos\theta] - [(k_r - 1/k_r](1 - co}$ $k_r = k_s/k_w,\ sin^2\theta = 1/N$ For cubic packing, N =1.5, and for rhombohedral packing, N=6.9	• For spherical particles • Assuming heat transfer in the particle contact is negligible • Large error when applying for dry soils
Woodside and Messmer (1961)	$k_t = (x_w - 0.03)k_w + (1.03 - x_w)\left[\frac{1-x_w}{1.03-x_w}\left(\frac{1}{k_s}\right) + \frac{0.03}{1.03-x_w}\left(\frac{1}{k_w}\right)\right]^{-1}$	Similar to above	• Combined both the series and parallel models

Reference	Formula	Definitions	Notes
Krupiczka (1967)	$k_t = k_w \left(\frac{k_s}{k_w}\right)^{A+Blog(k_s/k_w)}$	$A = 0.28 - 0.757\log(x_w)$ $B = -0.057$	- Valid only for : $0.215 \le n \le 0.476$
Johansen (1975)	$k_t = (k_{sat} - k_{dry}) * K_e + k_{dry}$	k_{sat} = thermal conductivity of soil in saturated conditions, depends on soil state:- $k_{sat} = k_s^{xs} 2.2^{xw} 0.269^{w_u}$, For saturated frozen $k_{sat} = k_q^q k_o^{(1-q)}$, For saturated unfrozen soils k_{dry} = thermal conductivity of soil in dry conditions, depends on soil type and porosity (see Farouki, 1981 for more details) $k_{dry} = \frac{0.135\rho_d + 64.7}{2700 - 0.947\rho_d}$ …… For dry natural soils $k_{dry} = 0.039 n^{-2.2}$ …… For dry crashed rocks k_e = normalized Kersten's number, depends on the degree of saturation $K_e = S$ ….. *For frozen soils* $K_e = 0.7 \log S + 1$ ….. For unfrozen coarse soils $K_e = \log S + 1$ ……. For unfrozen fine soils	- Apply for dry, saturated and unsaturated, frozen and unfrozen soils - The limitation could be in the k_e-S correlation formula
Cote and Konrad (2005)	$k_t = (k_{sat} - k_{dry}) * K_e + k_{dry}$	$k_{sat} = k_s^{xs} 2.24^{(x_w - \theta_u)} 0.6^{\theta_u}$, For saturated frozen $k_{sat} = k_s^{x_s} 0.6^{x_w}$, For saturated unfrozen soils $k_{dry} = X 10^{-\eta n}$ $K_e = \kappa S/1 + (\kappa - 1) S$ (see Cote and Konrad, 2005 for values of X, η, and κ)	- Similar to Johansen's equations but in more general formula that can be applied for a range of soils - One limitation is that it does not effectively account for the effect of saturation at low water content
Lu et al. (2007)	$k_t = (k_{sat} - k_{dry}) * K_e + k_{dry}$	$K_e = exp\{\alpha[1 - S^{(\alpha - 1.33)}]\}$, α = soil texture $k_{dry} = -an + b$, $a = 0.56$, $b = 0.51$ for $0.2 \le n \le 0.6$	- Developed based on Johansen's model - Work well for fine soils at low saturation

2.7 Electricity flow through soils

In conducting materials, electric charges are moved as a result of two internal forces; attractive or repulsive. The movement of charges are often accompanied by the transfer or change of the material internal energy. The rate of the work related to move a unit charge from one point to the other in the circuit represents the potential difference/ drop between these two points. The magnitude of this work or charge is measured in Volts. Like head or pressure in the hydraulic and temperature in the thermal systems, voltage is a very important parameter in conducting materials where there is flow of electricity.

In soils, the flow of electricity is complicated due to the complex nature of soil-water system itself and the difficulty of visualizing the wide range of soil particle sizes, types and composition and their magnitude of contribution in electric flow.

2.7.1 Electrical conductivity

The capability of many common materials to conduct electricity has long encouraged a number of researchers to carry out investigations for the purposes of addressing such an attractive phenomena. The German scientist, Georg Ohm, was one of those researchers who became inspired by the work of Fourier on heat conduction. In 1827, Ohm introduced a new mathematically-derived law for transfer of current through materials. Ohm's law suggested that the flow rate of a direct current, *I*, through a conducting body, is proportional to the voltage, *V*, across that body, as follow:

$$I = \frac{V}{R} \qquad (2.19)$$

Where *I* is the passing current (Amps), *V* is the voltage (Volts), and *R* is the resistance (Ohms).

The resistance is an electrical property that changes directly with the length of the conducting body and inversely with its cross-sectional area.

$$R = r_s \frac{L}{A} \qquad (2.20)$$

Where *L* is the conducting body length (m), *A* is the body area (m^2), and r_s is a coefficient expressing the resistivity of the body (Ohm. m). The reciprocal of the resistivity represents the electrical conductivity and it is expressed as:

$$\sigma = \frac{L}{R.A} \qquad (2.21)$$

Where σ is the electrical conductivity having units of (1/Ohm. m, mho/m, or S/m)

As long as most materials (solids, solutions, and porous media) do not exhibit considerable changes because of the measurement itself, Ohm’s law can be considered valid. In the literature reviewed, and in all the electrical tests performed on composite soils with varying clay/sand type and content, the principle of Ohm’s law applied.

In the geotechnical world, electrical conductivity has been used as an indicator or a measure of a range of soil’s physical (i.e porosity, mineralogy, saturation, clay content, and water content) and chemical (i.e salinity) properties. The electrical conductivity is also of a paramount importance in soil stabilization, particularly, in the electroosmotic treatment methods. The efficiency of the electro-osmosis method is a function of the electrical conductivity of a soil (Hamir et al., 2001, Mitchell and Soga, 2005).

2.7.2 Factors influencing electrical conductivity of soils

In a soil-water system, electrical conduction is mostly ionic, that is the solid phase itself is a very poor electric conductor (Rhoades et al., 1989). The movement of electric current mainly occurs through the inter-connected voids. However, the counter-ion clouds around charged particle surfaces can contribute to the ions-migration process, which arises from the relevant importance of the particle contacts and/or from the diffuse ionic double layer.

Given the above indications, and the available information on the electrical properties of soils, a range of possible factors can be recognised that can affect the electrical conductivity. These factors can be classified into three main categories; compositional, environmental, and test-related factors. A review of some of the common factors is presented below.

2.7.2.1 Fluid conductivity

Fluid conductivity plays an important role on soil’s overall conductivity. It represents one of the essential paths, and in some soils the only path for current to transfer through the soils. The magnitude of the electrical conductivity of fluid relies on the type of fluid, salt type and concentration in the fluid, and the temperature. An increase in temperature causes an increase in the ion-movement in fluid leading to an increase in the electrical conductivity of soil. A summary of the electrical conductivity of common fluids was presented in Dean (1999).

Investigations on coarse-grained soils (e.g. clean sands and sandstones) show that a soil's conductivity (σ_T) is directly proportional to its pore fluid conductivity (σ_w) (e.g. Archie, 1942). The parameter of proportionally was called by Archie (1942) as the formation factor (F) as:

$$\sigma_T = \frac{1}{F}.\sigma_w \qquad (2.22)$$

The Archie's formation factor depends on soil's porosity and fabric and will be discussed further in the next section. In coarse grained soils, the more conductive the fluid, the higher the overall soil's conductivity. For saturated fine-grained soils, the term apparent formation factor should be used instead as it involves an additional factor (e.g. effect of surface area of clays).

2.7.2.2 Porosity

The porosity is defined as the ratio of the void volume to the total soil volume. For saturated soils, the voids are often filled with fluid, and hence, it has an important effect on the geometrical flow of current through the soils (practically in soils of negligible surface conductance).

The influence of soil porosity on the overall electrical conductivity is dependent on the magnitude of both the conductivity of fluid and particle surface of the soil. Normally, in saturated soils of a very low surface conductivity (e.g. clean sands), an increase in porosity leads to an increase in the overall electrical conductivity and a decrease in the magnitude of the formation factor. However, this may be different where the contribution of clay surface conductivity is higher than that of pore fluid (i.e. in clays prepared with very low water conductivity) in that case, a decrease in the porosity can cause higher conductive clay grains to be closer, which eventually, increases the overall electrical conductivity. The former and latter cases were explored in the present study and the results are presented in chapter 6.

An empirical correlation between porosity and formation factor was observed by Archie (1942) using some experimental data on saturated sedimentary rocks as follow:

$$F = n^{-m} \tag{2.23}$$

Where n is the porosity; m is a constant, the cementation factor, which depends on the degree of cementation. Archie, based on his data, reported that the constant m ranges from 1.4 for loose sandstones to nearly 2 for the very highly-cemented sands. Wyllie and Gregory (1953) measured the electrical conductivity of artificially cemented coarse soils over a wide range of porosities. They reached a conclusion that Archie' formula (equ. 2.23) is a special expression of the more general equation:

$$F = C.n^{-d} \tag{2.24}$$

Where C and d are constants for a specific type of soil. While the constant d is dependent on the cementation state of soil, the constant C is governed by the porosity and formation factor of the actual un-cemented soil. By using the material of silica as a cementation factor, Wyllie and Gregory used a back analysis on their test data to find that the value of the constant C is equal to 4.3.

The applicability of Archie' model has been shown to apply to clean sands and sandstones, and in case where the contribution of matrix surface conductivity is anticipated to be insignificant (i.e when the pore fluid conductivity is very high). For more complex materials, such as clay rich soils, Archie's model needs to be either developed further or extended so that it can include the effect of negatively charged clays that constitute an additional key path for electric current to flow through fine soils.

2.7.2.3 Degree of saturation

The replacement of electrically non-conductive air with the very high conductive fluid (i.e. water) means that the size of pore spaces that formed one of the most important path for current to flow decreases and therefore the soil conductivity decreases. In some cases, the presence of non-conducting brines in conjunction with saturating water inside soil's pores also cause a reduction in the conductivity.

A number of researchers (e.g. Rhoades et al., 1976, 1981, Bohn et al., 1982, McCarter, 1984, Mualem and Friedman, 1991, Abu-Hassanein et al., 1996) carried out tests on partially saturated soils to suggest that the volumetric water content (θ_w) that is a function of saturation (S), gives a high correlation with the soil electrical conductivity. Figure 2.19 shows how the parameter (θ_w) correlates with the electrical resistivity index for tests on compacted clays from Rinaldi and Cuestas (2002).

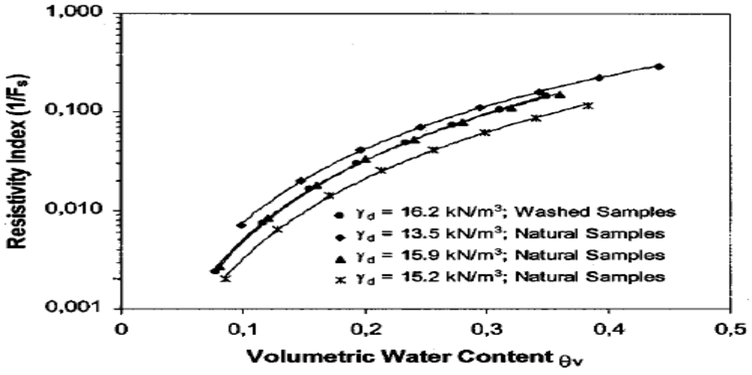


Figure 2.19: Electrical resistivity- volumetric water content relationship of compacted clays (from Rinaldi and Cuestas, 2002).

2.7.2.4 Stress

The influence of vertical effective stress on the magnitude of electrical conductivity of soils has been investigated by petroleum scientists and geo-physicists. For example, Wyble (1958) found that there is an increase in the cementation factor (m) of Archie's model with increasing confining stress. A similar finding was shown by Glanville (1959) who performed tests on soils of low permeability. Stesky (1986) carried out a wide range of experiments on natural and reconstituted rock samples subjected to stress of up to 200 MPa and concluded that increasing stress increments result in an increase in the value of electrical conductivity of both intact and synthetic samples (shown in Figure 2.20).

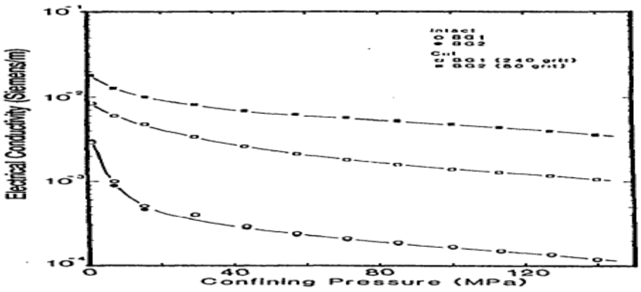


Figure 2.20: Effect of confining stress on electrical conductivity of natural and synthetic rocks

2.7.2.5 Temperature

The variation of temperature affects the mobility of ions in solutions. Increasing temperatures causes a decrease in the solution viscosity and an increase in the ion movements, and hence increasing the electrical conductivity. A summary of range of ion mobilities at different temperatures is presented in Dean (1999).

2.7.2.6 Clay type and content

The effect of clays on the overall soil conductivity is quite complicated, and a number of questions still remain (e.g. what is the magnitude of their contribution? What the main factors that are incorporated in the effect?). These need to be highlighted and discussed in more detail.

Clay grains themselves don’t conduct electricity. Dry clays have a very low electrical conductivity (Kibria and Hossain, 2012). It is well-known that clay grains inherently have negative charges on their surfaces and if they are in touch with water, a diffuse double layer forms on the external surfaces of the clay grains. The ion concentration in this zone is higher than that in the pore water (see Figure 2.21), and therefore, it will be a preferred path for the current to flow. The magnitude of the ion concentration in the vicinity of the clay surfaces depends on the clay type, content and its fabric, and also on the solution type. The distribution of ions can be more complicated in the case where the clay grains are close to each other.

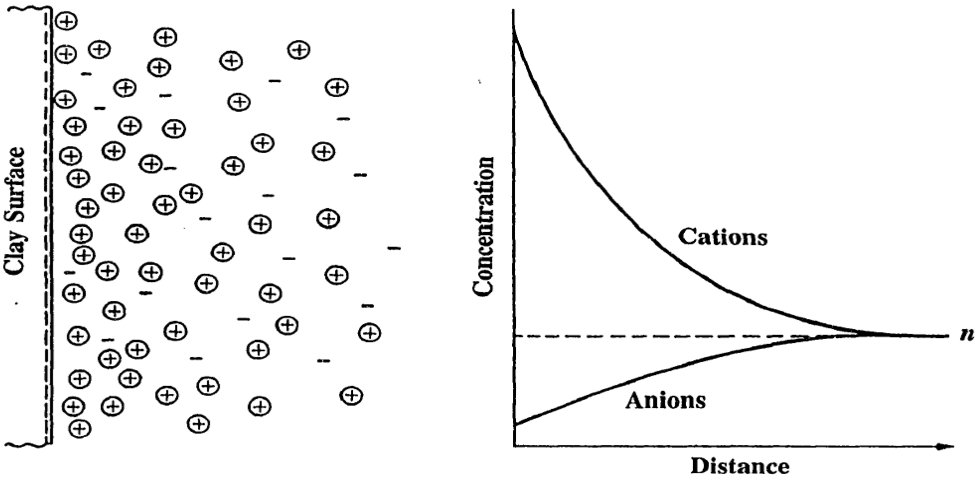


Figure 2.21: Basic concept of diffuse double layer in clays (adapted from Mitchell, 1976)

Mathematical theories and solutions on the diffuse double layer, the ion concentration near clay particles, and their interactions have been established and proved to be important in assessing the flocculation and dispersion in the structure of soil suspensions, and in addressing other characteristics, e.g. compressibility and swelling (see e.g. Gouy, 1910, Olphen, 1977, Mitchell James, 1993). Bikerman (1933) used the principles of the diffuse double layer to identify the term ‘‘surface conductivity’’ which emerges from the ion mobility in the vicinity of this layer. Stern (1924) stated that not all ions in the double layer zone have the ability to move and only some of them can participate in the conduction processes. In all cases, it is expected that the clay surface conductance due to the diffuse ionic layer can have an important role on the overall soil conductivity and the proper evaluation of the magnitude of this contribution is expected to be quite difficult.

Early practical investigations in the petrochemical industry by petroleum researchers and chemical colloidal scientists attempted to identify the role of the surface conductivity. They used the principles of Archie’s model that states the overall electricity conductivity of soils increases linearly with the pore water conductivity and as the soil’s porosity increases, the formation factor decreases (Winsauer and McCardell, 1953). Any deviation from this implies there should be a value for the surface conductivity.

Cremers et al. (1966) carried out electrical tests on suspensions (or gels) of salt-free montmorillonite clays to assess the effect of the clay concentrations and their ionic mobility on the sample electrical conductivity. They showed that in all montmorillonite clays, an increase in clay concentration implies an increase of the electrical conductivity (Figure 2.22), and sodium clay (Na) has more conductive electrical properties than calcium (K) even though the ionic movement in calcium type is much higher than its value in the sodium clay.

The electrical behaviour in Figure 2.22 can be described by the contribution of the bulk water and clay conductance. For clay gels and suspensions, adding clay leads to establishing another path for current to flow in line with the path of the pore water. If the suspension was prepared with water of very low conductivity, the preferred path for the electric current to flow will be along the more conductive clay path and then through the bulk water contained in pore spaces. As more clay is added, the solid per unit volume increases and the pore spaces decreases, and thus, the electrical conductivity increases. The rise in the electrical conductivity continues to increase with increasing clay concentration until the established bridges between clay particles reach a maximum at a specific clay concentration. This can be seen in Figure 2.23, particularly in cases where the soil is prepared with water of zero and 0.03 NaCl concentration. If, however, suspensions are mixed with higher bulk water conductivity, the current would flow more though the pore spaces and then through the very less conductive clay surfaces. In this case, adding clay results in a reduction in the suspension porosity that is the more preferable path of flow, and therefore, this can cause the electrical conductivity of the suspension to be decreased (see Figure 2.23 for water concentrations of 0.1, 0.7, 1, and 2.2 NaCl).

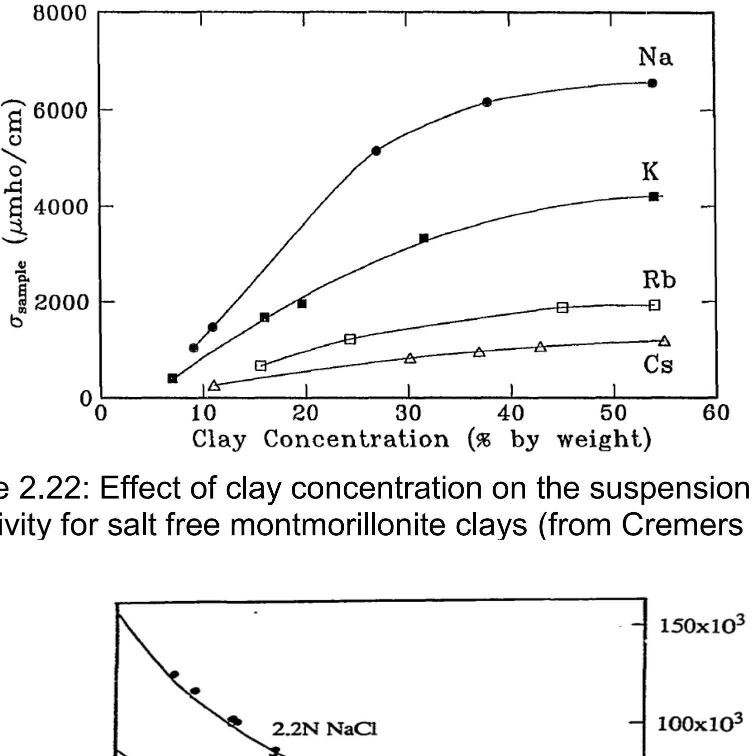


Figure 2.22: Effect of clay concentration on the suspension electrical conductivity for salt free montmorillonite clays (from Cremers et al., 1966)

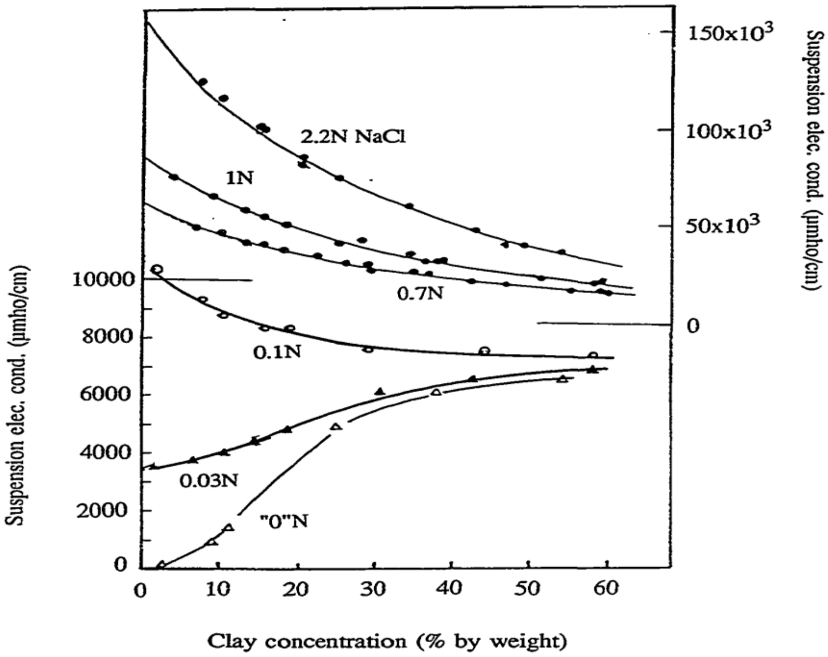


Figure 2.23: Effect of bulk water concentriation on the overall suspenstion conductivity of montmorillonite clays (from Cremers and Laudelout, 1966)

For water of intermediate conductivity, it might be expected that there will be an initial increase in the electrical conductivity when the clay content increases. This continues increasing until reaching a maximum and then when more clay is subsequently added, the electrical conductivity tends to decrease as the sample porosity decreases. While the latter case can obey the assumption of Archie's law, the former cannot.

Many petroleum scientists and chemists have reported that the relationship between the overall electrical conductivity (σ_T) and the pore water conductivity (σ_W) in sand-clay mixtures is different from that for clean sands. At low ranges of (σ_W), (σ_T) increases non-linearly, convex upwards and thereafter become a linear function of (σ_W) as shown in Figure 2.24. The transition point from the curved to the linear line is very likely to depend on water and surface conduction as well as soil tortuosity (porosity). This could be more complex when the clay surface conductivity is very high (i.e. when the pore water conductivity is very low).

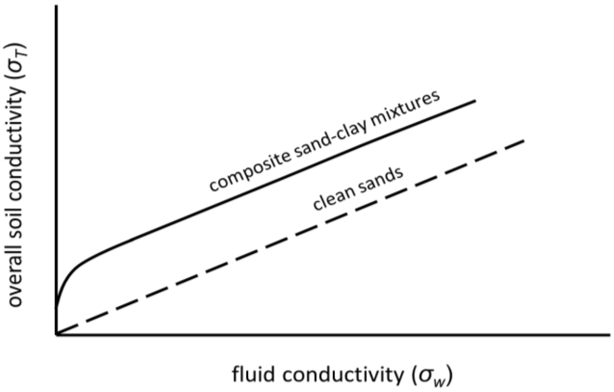


Figure 2.24: Overall soil conductivity – fluid conductivity relatonship in soils

From the above review, it can be concluded that the rate at which the electrical conductivity increases or decreases depends not only on the conductivity of the soil constituents but also on the particle structural arrangement (i.e. porosity and pore size distribution). The type and content of clay play an important role in the soil overall electrical conductivity because of the additional geometrical (i.e. specific surface area and particle size) and chemical (i.e. charge density) properties that are associated with their negatively solid particles. In this context and within the present research, composite soils with varying clay types and percentages prepared with tap and distilled water were used to assess how these clays effect the overall electrical conductivity.

2.7.2.7 Conductive solids

Some porous materials contain electrically conductive solids (e.g. metallic oxides and graphite). The mode of the electrical conduction in these solids is electronic and not ionic as in water, and therefore, their role in the current flow through soils can be significant. Fraser and Ward (1963) explored their impact on the overall electrical conductivity and showed that as their concentration increases, the effect increases as well. Identifying these conductive solids is of important in the interpretation of logs electrical resistivity, for instance.

2.7.3 Prediction of electrical conductivity

The complex nature of soil-water matrix and the difficulty in characterizing different types of soils with varying particle size and composition have limited the quantity of predictive electrical models. However, a number of theoretical and empirical models have been developed in the literature to predict the electrical conductivity of soils, specifically for coarse soils and shaly sandstones. They all vary in the underlying assumptions about the possible current path through soils and the magnitude of the contribution of the constituents.

The first empirical model for electrical conductivity was due to Archie (1942) as seen in equ. 2.22. This model has proved to give a reliable prediction for non-conducting soils (or coarse soils with a negligible surface conductivity). However, this model cannot be used for soils having particles with conductive properties (i.e. in composite sand-clay mixtures). Some models were then established in an attempt to account for the presence of clay in soils.

Of all the models, the work of Waxman and Smits (1968) has been the most widely accepted in interpreting the electrical conductivity of saturated sand-clay soils. By undertaking an investigation on 27 samples of shaly sands with a low clay content along with the data of Hill and Milburn (1956), Waxman and Smits concluded that the overall electric conductance in shaly sand formations can be possibly represented by two-resistors built in parallel to each other. One resistor represents the electrolytic pore liquid (water conductivity, σ_w). The other resistor represents the charged clay-resistance (surface conductivity, σ_s) that is associated mainly with the exchangeable cations. The equation is in the form of:

$$\sigma_T = X\,(\sigma_w + \sigma_s) \qquad (2.25)$$

Where x is geometrical factors similar to the inverse of the formation factor (1/*F*), σ_w, σ_s are the conductivity of water and particle surface, respectively.

The W-S model was developed further by considering that (σ_s) is a function of the exchangeable cations as:

$$\sigma_s = BQ_v \qquad (2.26)$$

Where *B* is the mobility of the cations in S cm^2 meq^{-1} and Q_v is cations-concentration per volume in meq cm^{-3}. Waxman and Smits used results of laboratory tests to create an empirical relationship for the parameter (*B*) as a function of the saturating water conductivity (σ_w) as:

$$B = 0.046\left[1 - 0.6exp(-\frac{\sigma_w}{0.013})\right] \qquad (2.27)$$

Additionally, Revil et al. (1998) showed that the parameter (Qv) can be linked to the cation exchange capacity and porosity as:

$$Q_v = \frac{(1-n)p_s CEC}{n} \qquad (2.28)$$

Where n is the soil's porosity; CEC is the cation exchange capacity (meq/g); and ps is the particle density of the soil.

In equ. (2.25), Waxman and Smits assumed that both (σ_w) and (σ_s) occur along conduction paths of equal tortuosity having the same geometrical factor. According to Bussian (1983), this is a conceptional issue in the W-S model as it means that the formation factor must be dependent on σ_s, which is not correct. In the W-S model, it is assumed that σ_T increases linearly with σ_w (Figure 2.24). Therefore, it should be expected that the work of W-S is only applicable to soils having a water conductivity equal to or higher than the particle surface conductivity.

Based on the Waxman and Smits model, Sen et al. (1988) developed a new model as an attempt to take into consideration pore fluids of low salinity. Sen et al. (1988) suggested that the low range of water salinity in the (σ_T - σ_w) relation in Figure 2.24, has slope greater than that for higher water conduction. The formula of Sen et al. model is:-

$$\sigma_T = n^m\left[\sigma_w + \frac{A\,Q_v}{1+\left(\frac{CQ_v}{\sigma_w}\right)}\right] + EQ_v \qquad (2.29)$$

Where *A*, *C* and *E* are constants in (S/m) (cm^3/meq) that depend on the fabric, EQ_v is an additional parameter that capture the effect of particle contacts conduction ≈ 0 in most rocks. By applying equation 2.29 to sandstone cores containing fluid of different salinities, Sen et al. proposed the following equation:

$$\sigma_T = n^m \left[\sigma_w + \frac{1.93\, m\, Q_v}{1 + (\frac{0.7}{\sigma_w})} \right] + EQ_v \qquad (2.30)$$

Sen et al. depended on data from Hill and Milburn (1956) and Waxman and Smits (1968) in the assessment of their model. According to Sen et al. (1988), the constant (*m*) in equ. (2.30) increases with increasing clay content attributing that to an increase in soil's tortuosity as the clay content increases. Generally, Sen et al. show a good fit for all the data with $m \approx 2$.

It should be stated that most of the electrical models presented in table 2.5 including Wamxman and Smits and Set el al. models were developed for the petrochemical industry focusing on shaly sandstones with limited clay content. in composite soils, the clay can be significant in amount and type and, the pore fluid conductivity can be significantly less than that of the clay; thus the linear relationships of ($\sigma_T - \sigma_w$) may not be valid.

Table 2.5: Common theoretical and empirical electrical conductivity models

Reference	**Formula**	**Definitions**	**Notes**
Theoretical models			
Maxwell (1887)	$\frac{\sigma_w}{\sigma_T} = \frac{3-n}{2.n} = F$	σ_w = water conductivity σ_w = overall soil conductivity *F* = formation factor *n* = porosity	• Non-conductive particles of spherical shape • highly dilute gels (e.g. no particle contact exists) • F is independent of particle size • Not valid for particles having conducting characteristics or their " external surfaces" are conductive
Burger (1919) and Fricke (1924)	$\frac{\sigma_w}{\sigma_T} = \frac{(x+1)-n}{x.n} = F$	*x* = 2 for spherical particles and less than 2 for other shapes	• Non-conductive particles of spherical shape • Very dilute gels or suspensions • Not applicable for conductive particles

Reference	**Formula**	**Definitions**	**Notes**
Empirical models			
Archie (1942)	$\frac{\sigma_w}{\sigma_T} = n^{-m} = F$	*m* = cementation factor = 1.3 – 2	• Non-conductive particles (i.e. sandstones and clean sands) • For high water conductivity, the results are more reliable
Wyllie et al. (1953)	$\frac{\sigma_w}{\sigma_T} = C.n^{-d} = F$	*C* = constant = 0.95-1.25 for Wyllie et al. data. *d* = constant depending on the cementation state= 4.2 for silica sands	• The more general equation of Archie's model
Patnode and Wyllie (1950)	$\sigma_T = A.\sigma_w + B$	*A* = slope of the relation, which equals to the inverse of the formation factor (*F*) *B* = the intersect of the relation, capture effect of conductive solids	• Assess the contribution of the conductive solids on the overall soil conductivity.
Winsauer et al. (1952)	$\sigma_T = N.(\sigma_w + \sigma_s)$	*N* = constant = 1/*F* = n^m σ_s = surface conductivity of solid particles in soils	• Consider the role of water and conductive particles. • σ_s depends on the type and content of clay available
Wyllie and Southwick (1954)	$\sigma_T = \frac{\sigma_s\sigma_w}{A\sigma_s + B\sigma_w} + C\sigma_s + D\sigma_w$	*A, B, C, and D* = geometrical constants for data fitting	•
Waxman and Smits (1968)	$\sigma_T = N.(\sigma_w + BQ_v)$	*N* = 1/*F* *B* = empirical constant of the pore water conductivity (σ_w). Q_v = cations-concentration per volume that depends mainly on the cation exchange capacity (*CEC*)	• Produced based on the data of Waxman and Smits (1968) and Hill and Milburn (1956) for shaly sandstones with low clay content • Applicable only in the case where the water conductivity (σ_w) is higher or equals to the particle surface conductivity (σ_s) in which the relation between overall soil and water conductivity is linear (e.g. for clean sands and sands with low

Reference	Formula	Definitions	Notes
			clay of low cation exchange capacity, CEC) • Not applicable for soils having non-linear $(\sigma_T - \sigma_w)$ relation in which the (σ_w) is less than the conductivity (σ_s) (i.e. soil of high CEC such as montimoriolonite clays)
Rhoades et al. (1976 and 1981)	$\sigma_T = T\,\theta_w\,\sigma_w + \sigma_s$	*T* = constant that depends on the volumetric water content (θ_w).	• Produced mainly for partially saturated materials and it has very good agreement when the water conductivity is higher than 0.4 S/m
Bussian (1983)	$\sigma_T = N.\sigma_w \left(\frac{1-\sigma_s/\sigma_w}{1-\sigma_T/\sigma_s}\right)^m$	See the above definitions	• It is true that this formula can work for all cases (i.e. low and high water conductivity), the only difficulty lies in the conductivity of soil particles (σ_s) that depends on other properties which can only be known from a more thorough comprehension of the electro-chemistry phenomenon in soils (Bussian, 1983)
Sen et al. (1988)	$\sigma_T = N.\left[\sigma_w + A\,Q_v/1 + (\frac{CQ_v}{\sigma_w})\right] + EQ_v$	*A* = constant = 1.93* *m* *CQ*CQ_v = fitting constant = 0.7 EQ_v = additional parameter that capture the effect of particle contacts conduction ≈ 0 in most rocks	• Applicable for low and high water salinities • Based on the Waman and Smits model • Produced based on the data of Waxman and Smits (1968) and Hill and Milburn (1956) for shaly sandstones with low clay content.

2.8 Analogy between soil's conductivities

A review of the soil's conductivities in sections 2.5, 2.6, 2.7, shows an analogy between them such that the flux (fluid flow, heat flow, current transfer) is directly proportional to a driving potential.

In addition to that, soil conductivities are seen to be affected by similar compositional and environmental factors. For example, the flow of water though soils is essentially a function of pore spaces sizes and its geometry. The current, in most soils, also transfers though the soil pore contained water and the volume and distribution of the pores govern the electricity transfer path. Therefore, a number of researchers (e.g. Archie, 1942, Lovell and Ogden, 1984) assessed the nature of the relationship between the hydraulic and electrical conductivity taking into account the effect of pore size and geometry and used the formation factor (*F*) as an indicator in the relationship. Thermal conductivity, in turn, is also influenced by the properties of the water present in soil's pores and solid particles and their volume fraction.

The hydraulic, thermal and electrical conductivity are also a function of the same environmental and physical factors (e.g. water content, dry density, degree of saturation, porosity and void ratio, temperature). Each factor has a different effect on conductivity in that increasing the factor can result in an increase or decrease in conductivity depending on the composition of the soil and pore fluid. For instance, an increase in temperature leads to an increase in all conductivities, however, increasing density causes a reduction in the hydraulic conductivity, an increase in the thermal conductivity, and either an increase/decrease in the electrical conductivity based on the electrical conductivity of the pore water.

Table 2.6 summarizes some of the common factors that affect the hydraulic, thermal and electrical conductivities. The expected variation in each conductivity that is associated with a variation in the factor is presented, that is based on the literature review and the current understanding of the soil's conductivity. It is useful to see how these factors affect conductivity and take note of the parameters that impact one and not the other.

Table 2.6: Effect of some factors on the hydrauic, thermal and electrical conductivity of soils

Factors	Property	Variation	Effect on k_h	Effect on k_t	Effect on σ_T	Notes
Compositional factors	Nature of permeant	viscosity (↗)	↘	↘	↘	higher viscosity, means a lower charges mobility, so a lower fluid, thermal and electrical conductivity. increasing electrical conductivity of pore water will increase the overall conduction
		σ of pore fluid (↗)	— (no structure change)	—	↗	
	Particle size	↗	↗	↗	↗	The larger the particles size, the larger the pores spaces between them, thus an increase in conductivity
	Sample size	↗	↗	↗	↗	Larger samples might include more discontinuities, thus more water, heat and current paths
Environmental factors	Water content (w_c)	↗	↗	↗ ↘	↗	An increase in water content leads to increasing soil's hydraulic and electrical conductivity but for thermal it depends on the saturation state of soil (for partially soil, it increases and for fully saturated soil, it decreases)
	Degree of saturation (S)	↗	↗	↗	↗	An increase in degree of saturation leads to the low conductive air to be. Replaced by the high conductive water.
	Porosity (n)	↗	↗	↘	?	Increasing soil porosity can either increase or decrease the electrical conductivity depending on the dominating phase conductivity
	Temperature (T)	↗	↗	↗	↗	An increase of temperature means increasing all conductivity parameters
	Density (γ)	↗	↘	↗	?	Any increase in soil density leads to a decrease in the void ratio, thereby a reduce in hydraulic conductivity with increasing of thermal conductivity
	Void ratio (e)	↗	↗	↘	?	
	Effective stress (σ)	↗	↘	↗	?	Stress reduce the void ratio, porosity and increasing density which in turn decreasing hydraulic, increasing thermal conductivity. Its effect on the electrical conductivity is expected to be dependent on the dominating phase conductivity
	Surface electrical Conductance	↗ (*CEC*)	?	?	↗	No change in k_h and k_t if the pore structure is unchanged
	Hydraulic gradient (i_h)	↗	↗ ↘	?	?	if micro-cracks occur, k_h increases; and if pore clogging forms, its decreases
	Thermal gradient (i_t)	↗	?	?	?	Under thermal differences, water will move from hot end to

Factors	Property	Variation	Effect on k_h	Effect on k_t	Effect on σ_T	Notes
						cold one in a continues circulation
	Electrical gradient (i_e)	↗	?	?	?	Increasing the electrical gradient can be expected to alter the structure of soils specially when use DC current in measurements
? :- The effect of the parameter on the behaviour is not fully known and may be expected.						

Table 2.7: The typical range of soil's conductivity

Parameter	Symbol	Units	Coarse-grained soils		Fine-grained soils	
			Minimum	Maximum	Minimum	Maximum
Porosity	n	-	0.1	0.4	0.2	0.7
Hydraulic conductivity	k_h	m/s	$1 * 10^{-5}$	1	$1 * 10^{-11}$	$1 * 10^{-6}$
Thermal conductivity	k_t	W/m. °C	1.5	4.5	0.25	2.5
Electrical conductivity	σ_T	S/m	0.001	1.0*	0.01	1

2.9 Summary

The basic description of composite or intermediate soils is given. The available studies of these soils in the literature review were highlighted. More investigations need to be carried out on a range of composite soils so that the understanding of these soils is increased not only in the scheme of soil classification system but also in the engineering behaviour.

The hydraulic, thermal and electrical conductivities of soils, the common factors influencing them, the different laboratory and in situ methods used for measuring them, and the most common predictive methods were all reviewed. It is shown that there is an analogy between soil's conductivities in that all conductivities are driven by a similar process during their transfer from one region to another which could be a good point to design new equipment to determine the conductivity of soil. Moreover, all of soil’s conductivities have seen to be affected by similar compositional, environmental and physical factors.

In the remaining chapters of this thesis, the equipment used to determine the conductivity of composite soils are described in detail and the effect of a soil’s compositional and physical properties on each conductivity is assessed.

Chapter 3

Materials Used, Laboratory Testing Program and Equipment Design

3.1 Introduction

The information about the main materials used to form composite soils, the equipment used to determine the hydraulic, thermal, and electrical conductivity, their design criteria, principles and components description, is provided. The test methods and procedures used in the determination of soil' conductivities are described in detail.

3.2 Materials used to form composite soils

Investigation of the contribution a soil's composition makes to its mechanical, hydraulic, thermal and electrical properties is often based on artificial soils. This is because of the fact that the variations in composition and fabric of any natural soil are so great as to mask the intrinsic behaviour. The composite soils used in the current research were formed of fine-grained soils:- five types of clays; kaolinite, bentonite, illite, sepiolite, and attapulgite, mixed with coarse-grained soils:- three sands; uniform medium sand (fraction C), uniform fine sand (fraction D), and the last one consist of mix of uniform sands (5% fractions A, 40% B, 40% C, and 15% D). The details of the materials used are presented in Table 3.1.

Kaolinite is one of the most common minerals found in natural clays (Grim, 1959) and has a consistent and uniform mineralogy with low organic content (Yukselen-Aksoy and Reddy, 2012). Bentonite *CB*, calcium type, was used because of its importance in many engineering applications because of its high capability as a lubricant agent used in construction processes. A low plasticity clay, illite, and high plasticity clays, sepiolite and attapulgite, were also used to provide a range of clay types.

Table 3.1: The properties of materials used to form the composite soil mixtures

Materials		Atterberg Limits	PSD	specific gravity (Gs)	Mineralogical composition	Origin (supplier company)
Fine grained soils	Kaolinite	I_L= 56% I_P= 33% PI= 23%	% < 2μ = 34.0	2.60	Kaolin = 94% Mica = 4% Quartz = 2%	Immersly Ltd, UK
	Bentonite *CB*	I_L = 105% I_P = 48% PI= 57%	% < 2μ = 29.0	2.55	Montmorillonite = 88% Mica = 5% Feldspars = 5% Quartz = 2%	RS Minerals Ltd, UK
	Illite	I_L = 37.6% I_P = 20% PI= 17.6%	% < 2μ = 42.9	2.67	100% natural illite clay	Aromantic Ltd, UK
	Sepiolite	I_L = 118% I_P = 86.5% PI= 31.5%	%< 2μ = 27.0	2.30	Sepiolite = 60% Other clays = 40%	RS Minerals Ltd, UK
	Attapulgite	I_L= 225% I_P= 126% PI= 99%	%< 2μ =	2.08	Attapulgite = 85% Other clays = 15%	RS Minerals Ltd, UK
Coarse grained soils	Fine sand (Fraction *D*)	-	(150 – 300) μ	2.63	Quartz = 98% Other minerals=2%	David Ball Group Ltd, UK
	Medium sand (Fraction *C*)	-	(300 – 600) μ	2.64	Quartz = 97% Other minerals=3%	David Ball Group Ltd, UK
	Mixed sand (5% A + 40% B + 40% C + 15% D)	-	(150 – 2360) μ	2.65	Quartz = 98.2% Other minerals=1.8	David Ball Group Ltd, UK
Water	De-aired water	-	-			Geotech lab/ University of Leeds
	Tap water	-	electrical conductivity = 0.0343 S/m			Yorkshire Water, UK
	Distilled water	-	electrical conductivity = 0.00047 S/m			Geotech lab/ University of Leeds

3.3 Experimental equipment for determination of hydraulic conductivity

The coefficient of hydraulic conductivity (k_h) of composite soils were determined indirectly from consolidation tests and directly using Darcy's law with constant head tests. These were to study the impact the characteristics of composite soils have upon k_h. An assessment of the hydraulic conductivity by the two-methods allows a comparison to be made between them and to examine the effect of sand content on the reliability of the hydraulic conductivity determined from consolidation data. In this section, the equipment used and procedures followed for assessment of k_h from consolidation tests are presented.

3.3.1 Design new consolidation cell

The conventional 20mm high standard consolidation cell was designed for the purpose of testing natural homogeneous clays. It is recommended that the maximum particle size is 10% of the sample's height but given the amount of sands found in the samples, a 20mm sample height was considered unsuitable to ensure that scale effects did not impact the results. Further, to ensure saturated conditions, a slurry-like mixture was used to form the reconstituted samples, which meant a sample would undergo large volume changes under the initial loading. For these reasons, new rigid-wall consolidation cells were designed.

3.3.2 Design principles and description of the consolidation cell

The engineering principles behind the design of the new consolidation cell are quite similar to those prescribed in BS EN ISO 17892-5:2017 and ASTM D2435-11 standards in which a cylindrical sample of saturated soil is laterally confined, subjected to vertical axial stresses, and permitted to drain freely from both top and bottom surfaces. The consolidation cell, shown in Figure 3.1, was designed to comply with the assumptions of Terzaghi's theory for one dimensional consolidation of soils.

The cell, shown schematically in Figure 3.1, consists of a solid acrylic cylindrical cell (2) to contain and laterally restrain a soil sample; a stainless steel base (6); bottom drainage systems (4); and a loading cap (1). The cell body is made of clear solid acrylic with 15mm wall thickness which could withstand vertical pressures up to 1300kPa. An O-ring (5) sits between the cell base and the acrylic tube to ensure a complete seal during the operation. The cell was designed to sit in a standard oedometer rig (Figure 3.1) which restricted the outer diameter to 134mm and height to 126mm. Drainage was allowed from top and bottom of a sample using porous discs to transfer the applied stress to the sample and to provide a drainage path. The British standard recommends using a screen of filter papers placed between the sample and the porous discs. However, this may be disadvantageous. Head (1982) state that when using such screen, fine soil grains can be enmeshed in the fibre pores of the filter screen, leading to clogging of the pores and impeding the drainage of water, and thereby this can adversely affect the measurements.

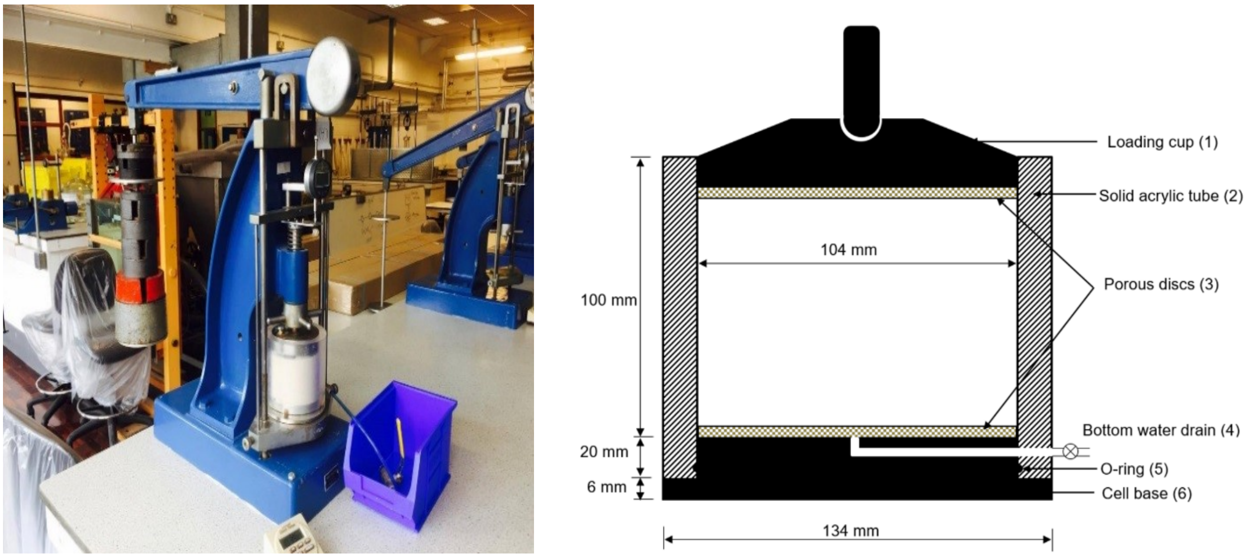


Figure 3.1: The new consolidation cell

3.3.3 Friction in the new consolidation cell

Ideally, the sample used for consolidation tests should be as large as possible in order to represent the soil's fabric and composition. However, the effect of side friction increases when the sample height to diameter (H/D) ratio increases. The British Standard, BS EN ISO 17892-5:2017, indicates that an H/D ratio between 0.25 and 0.33 is acceptable. ASTM-D2435-11 specifies a minimum H/D ratio of 0.4. Thus, to minimize the frictional influence, samples with, H = 44 mm and D = 103.8 mm, H/D = 0.42, were used and, in addition to that, the internal surfaces of the cell were lubricated with a grease.

3.3.4 Sample preparation and setup for consolidation tests

The composite soil samples were prepared as slurry with a water content 1.5 times the liquid limit to ensure that they were fully saturated but sufficiently viscous to prevent segregation. A soil with varying coarse (sands) and fine (clays) grained fractions was mixed together dry for about half hour using a motorised rotary mixer. After greasing the cell, the slurry-like mixture was poured into the cell in layers up to the desired height. The cell was vibrated using a shaking table to eliminate any entrapped air and the sample sealed and stored overnight to ensure a homogenous sample. A loading cap with a porous disc was placed on top of the soil slurry. The assembled cell was centrally placed on the platform of the loading frame to be ready for the consolidation processes.

3.3.5 Consolidation test procedures and conductivity calculations

One dimensional consolidation experiments using the new consolidation cells were carried out following similar procedures described in the British standard (BS EN ISO 17892-5:2017), except that the initial vertical stress on the sample was kept at 2.5 kPa. This relatively low stress was selected so as to prevent slurry being squeezed out of the cell through the gap between the loading platen and cell walls. Stress increments were applied up to maximum stress of 1280kPa. Each increment was added when the primary consolidation for the current load was accomplished. In general, this depended on the type of soil and its plasticity, and it varied from four days for bentonite samples, to three days for sepiolite and one day for kaolin and illite.

At a given effective stress (σ_v'), the hydraulic conductivity for each load increment was obtained indirectly using the assumptions of Terzaghi' s one-dimensional consolidation theory. Both coefficients of consolidation (c_v) and volume compressibility (m_v) were used to determine the hydraulic conductivity (k_h), as expressed by:

$$k_h = c_v m_v * 0.31 * 10^{-9} \qquad (3.1)$$

This equation has been widely accepted and used extensively as a method to determine the k_h (e.g. Sivapullaiah et al., 2000, Horpibulsuk et al., 2007, Yong et al., 2009, Mishra et al., 2011, Watabe et al., 2011). Two common methods are used to determine the coefficient of consolidation, c_v, based on the primary consolidation; Casagrande's and Taylor's method. Casagrande used time corresponding to the 50% primary consolidation (t_{50}) in the calculation of c_v; Taylor used t_{90}. Head (1982) stated that it is better to determine c_v from the method with (t_{50}) rather than Taylor's method with (t_{90}) because of the agreement found with the theoretical curve. However, Tavernas (1983) proved through an investigation on natural soft clays that k_h values determined by Taylor's method are closer to the actual reading than those determined from Casagrande's method. Hence, the coefficient of consolidation, c_v, in the tests was determined based on the Taylor method by using the time corresponding to 90% primary consolidation in the square-root plot (t_{90}). Typical calculations involved in the consolidation tests are presented in Table 3.2 for kaolinite clay. More details about the calculations of the parameters presented in Table 3.2 are given in Head (1982).

Table 3.2: Typical calculations for hydraulic conductivity based on consolidation test for kaolinite (FSK100)

Increment No	Void Ratio				Volume compressibility (m_v)				Coefficient of consolidation (c_v)						Hydraulic conductivity
					Incremental change			mv =							
	stress (σ_v) kN/m^2	Settlement (ΔH) mm	$\Delta e = Fx \Delta H$, $F =$	$e = e_o - \Delta e$	δe	$\delta \sigma v$ kN/m^2	(1+e_1)	$\frac{\delta e}{\delta \sigma v} x \frac{1000}{1+e}$ m^2/MN	t_{90} min	$H = Ho - \Delta H$ mm	$\hat{H} = H_1 + H_2 / 2$ mm	$(\hat{H})^2$ mm^2	$c_v = 0.112x (\hat{H})^2 / t_{90}$ m^2/year	c_v after correction of temperature $c_v = c_v * 0.980$	$kh = m_v * c_v * 0.31 * 10^{-9}$ m/s
0	0	0.000	0.000	2.147	0.000	0	-	-	-	65.0	-	-	-	-	-
1	2.5	6.520	0.316	1.832	0.316	2.5	2.832	44.596	200	58.5	61.7	3811.8	2.135	2.092	2.89E-08
2	5	7.590	0.368	1.780	0.052	2.5	2.780	7.455	186	57.4	57.9	3357.6	2.022	1.981	4.58E-09
3	10	8.983	0.435	1.712	0.067	5	2.712	4.973	179	56.0	56.7	3216.4	2.013	1.972	3.04E-09
4	20	11.053	0.535	1.612	0.100	10	2.612	3.837	170	53.9	55.0	3023.0	1.992	1.952	2.32E-09
5	40	13.314	0.645	1.503	0.109	20	2.503	2.187	152	51.7	52.8	2789.6	2.055	2.014	1.37E-09
6	80	16.000	0.775	1.373	0.130	40	2.373	1.370	145	49.0	50.3	2534.4	1.958	1.918	8.15E-10
7	160	18.384	0.890	1.257	0.115	80	2.257	0.639	140	46.6	47.8	2285.6	1.828	1.792	3.55E-10
8	320	21.023	1.018	1.129	0.128	160	2.129	0.375	138	44.0	45.3	2051.8	1.665	1.632	1.90E-10
9	640	23.723	1.149	0.999	0.131	320	1.999	0.204	135	41.3	42.6	1817.1	1.507	1.477	9.36E-11
10	1280	26.223	1.270	0.878	0.121	640	1.878	0.101	130	38.8	40.0	1602.2	1.380	1.353	4.22E-11

3.4 Experimental equipment for determination of direct hydraulic, thermal and electrical conductivity of composite soils

As the central focus of the present research is to experimentally investigate the hydraulic, thermal and electrical conductivity of composite soils, and these all require similar equipment in which a potential can be applied across a soil sample, it is possible to develop an equipment that can determine all of these properties. It is known that flow mechanism of fluids, heat and electricity through any soil has a similar process during its transfer from one region to another. They all obey the principles of one-dimensional flow under steady state conditions. This was a good start to design and build a single integrated equipment used for simulating water, heat and electricity flows in soils in direct and coupled form of flow that allows for their corresponding conductivities to be measured directly.

3.4.1 Design critera and requirments of conductivity equipement

The design concept of the conductivity testing equipment had to be guided by the following demanding requirements:

- The conductivity equipment would allow the consolidation of a saturated soil with varying composition and particle sizes and types.
- The flow due to a hydraulic or electric or thermal potential could be measured independently.
- The cell should be designed to prevent soil consolidation and movement of fine under water flow.
- Leakage between the piston and cell wall that may occur during the process of consolidation or when measuring conductivity should be avoided.
- The cell should be made of thermally and electrically insulated material such as engineering acrylic or high density polyethylene in order to ensure that the cell does not affect the flow of heat or electricity during a test.
- An appropriate wall thickness should be considered to avoid any undesired wall deformation or crack that may arise in the process of consolidation.

- ❖ A high-quality insulation with a suitable thickness should be applied radially around the cell and also at the cell base so that radial and basal heat loss can be reduced to a minimum quantity.
- ❖ Electrodes, valves, pipes, flow lines and reservoirs being used must be resistance to corrosion.
- ❖ It should be possible to operate over a range of hydraulic, current or temperature gradients.
- ❖ Flexibility where possible shall be provided in the design of the equipment so that it could be used to investigate other soils in future research.

3.4.2 Design principles

A single integrated cell was designed to combine three different systems, hydraulic, thermal, and electrical. The engineering design of the new conductivity cell was based on the application of Darcy's, Fourier's, and Ohm's law of one-dimensional flow under steady-state condition.

In the hydraulic conductivity system (Figure 3.2), water is induced to flow in laminar one-dimensional conditions across a consolidated soil sample under a constant potential difference (a constant hydraulic gradient). When a steady state of flow is established, the volume of water flowing through the sample in a known time is measured. The coefficient of hydraulic conductivity, k_h, is calculated using the theory of Darcy's law using equ 2.6, section 2.5

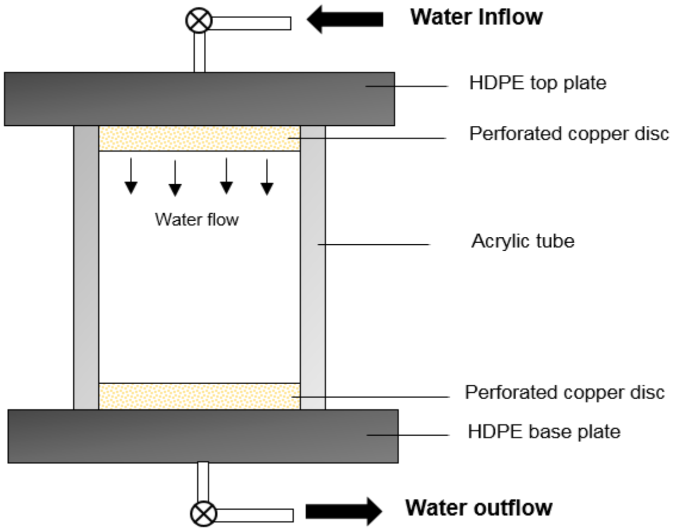


Figure 3.2: Hydraulic conductivity principles

In the thermal system, in order to create a scenario of heat flow through a soil sample, it is essentially to apply a thermal gradient across the sample. This can be achieved by placing a heating source (heater element) at one end of a cylindrical soil sample (e.g. at the bottom) with almost the same diameter as the soil sample, as shown in Figure 3.3. It is known that the rate of radial and basal heat loss have an effect on the measurements of the thermal conductivity, and thus it should be minimised. To do that, and to ensure unaffected one-dimensional flow, the cylindrical face of the sample was thermally insulated by surrounding the cell with a very low thermal insulating material (polyethylene). Thus, the heat generated will flow vertically from the bottom of the soil sample towards its top without any impendence. The thermal conductivity is determined using Fourier's law by measuring the temperature variations at four different points along the sample:

$$k_t = QL/A\Delta T \qquad (3.2)$$

Where Q is the rate of flowing heat (watts), L is the sample length (m), A is the cross-sectional area of the sample (m^2), and ΔT is the temperature difference at any two points along the sample (C^o).

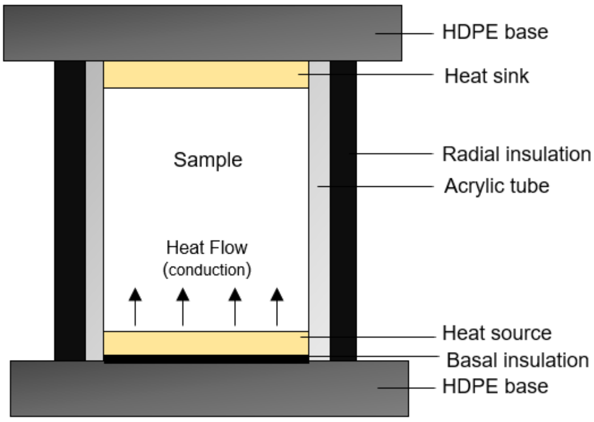


Figure 3.3: Thermal conductivity principles

The general idea in the electrical system is to create a one-dimensional electrical field by applying a constant voltage difference along the axis of a cylindrical soil sample, as seen in Figure 3.4. In order to make up this process, two copper electrode discs are fitted to the both ends of the sample (one at the top and the other at the bottom of the sample). A voltage difference is applied across the sample by using a lab power supply, and the resulting current is measured. The electrical conductivity of the soil sample is then determined following the applications of the Ohm's Law depending on the sample's resistance, *R* (see section 2.7.1)

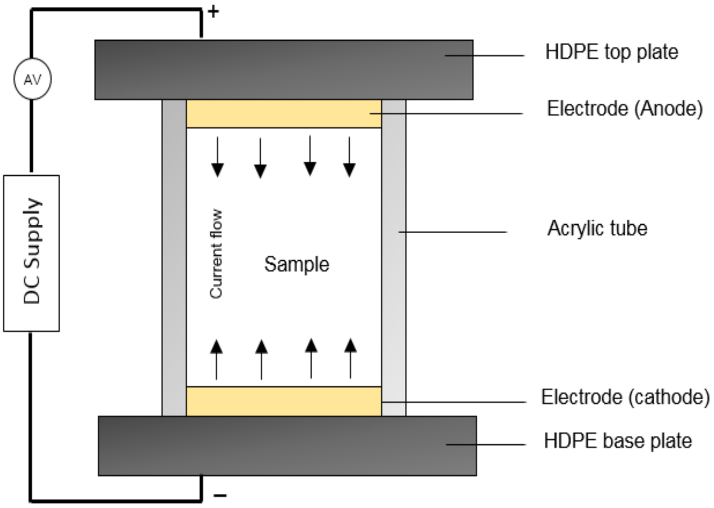


Figure 3.4: Electrical conductivity priciples

3.4.3 Description of the conductivity testing system

Although combining consolidation, hydraulic, thermal, and electrical measurements in a single cell has various advantages in term of time, cost, and sample disturbance, it is a complicated and challenging task. Each component of the cell had to be compatible with the principles of the test so that the components did not affect the results. For example, it is not possible to use the standard porous stones made of aluminium oxide for thermal conductivity as they reduce the heat transferred from the heat source to the sample because they have a low thermal conductivity. A perforated metal disc of high thermal conductivity properties was used instead. Thus, the cell components were selected so that they could work well with hydraulic, thermal and electrical conductivity systems.

Two new cells were designed and two conductivity testing systems were constructed for the determination of hydraulic, thermal and electrical conductivities of composite soils. The overall conductivity testing system, shown in Figure 3.5, consists of nine components; conductivity cell body (1), triaxial loading frame (2), constant pressure units (3), volume change indicator (4), lab supply device (5), temperature sensors (6), heater element (7), data logger unit (8), electrical multimeter device (9). It is more useful to describe these components in more detail based on their individual testing system.

Figure 3.5: A photo for the whole conductivity testing system

3.4.3.1 Conductivity cell

The conductivity cell is the main component in the conductivity testing system. The cell, shown schematically in Figure 3.6, consists of a cylindrical rigid body (12) that hosts a sample with two top and base plates (5, 20) held in place by four bolts (13). The cell body was made of an acrylic tube with 15 mm wall thickness, 134 mm outer diameter, and 325 mm height. Acrylic material was used as it offers a good thermal and electrical insulation ($k_t < 0.2$ W/m. ^{o}C, $\sigma_T < 0.0001$ S/m). Acrylic also has the advantage, it is simple in fabricate. The top and base plates were made of high density polyethylene (HDPE) material with a thickness of 40 mm and a diameter of 225 mm. Suitable O-rings (6) were accommodated on the top and bottom faces of the cell plates to ensure a complete seal, permitting the cell to be well pressurised through the hydraulic measurements.

The conductivity cell was fabricated to create a rigid wall permeameter which assumes that the application of Darcy’s Law is valid. A rigid-wall permeameter was selected for three reasons. The first was related to the nature of the tests that were conducted in the equipment. Samples were subject to three different tests (hydraulic, thermal and electrical tests) and the rigid-wall cell offers a medium of freedom for carrying out such tests. The second was to enable a soil sample to be tested directly in the cell. Consolidate a sample in an external mould, extrude it, prepare it and then set it up in the equipment take too long resulting in a highly disturbed sample. The third reason was that a range of vertical stresses can be applied on the sample to determine the effect of some of the soil physical properties (i.e. void ratio and porosity) on the conductivity.

Prior to the measurement of conductivities, the soil sample was consolidated to a desired condition (e.g. to a certain stress or density) using a constant rate of strain (CRS), in which the vertical strain of the soil sample was applied at a constant rate.

Perforated copper discs (10, 15) were placed on both top and bottom faces of the sample to act as an adequate hydraulic, thermal and electrical conductor. These discs permit water to drain during the processes of consolidation and hydraulic measurements. In the thermal testing procedures, the bottom disc formed the heat source and the top one, a heat sink. These two copper discs also served as electrodes (anode and cathode) in the measurements of electrical conductivity to induce a one-dimensional electrical field across the sample. Since the anode would degrade if the test take long time, it was better to place it at the top of the soil sample so it could be easily replaced.

At the top of the cell, a perforated rigid piston (8) made of HDPE material and guided by O-ring (9), was used to apply vertical stress to the soil sample. HDPE material was used as an insulator since it prevents any possible electrical conduction during the electrical conductivity measurements. The water can drain from both top and bottom of the sample during the consolidation. This gives the possibility of accelerating the process of dissipating pore water pressure of the sample.

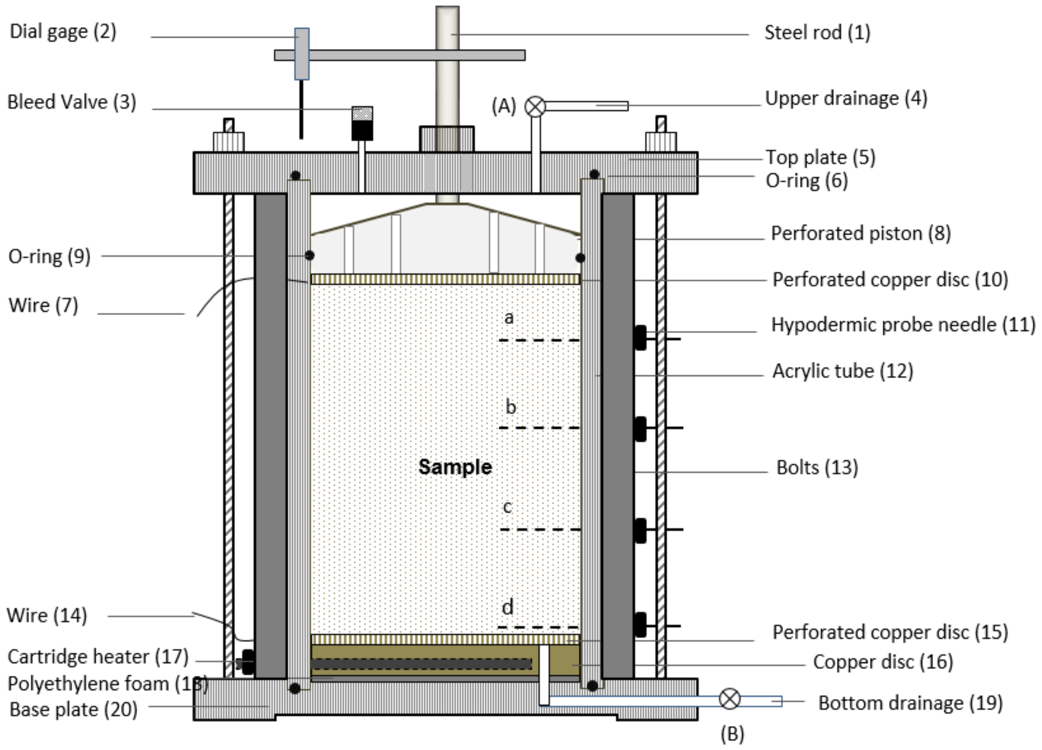


Figure 3.6: Schematic digram of the new conductivity cell

At the base of the cell, a cartridge heater element with internal thermocouple (17) was inserted into a non-porous copper disc (16) to act as a uniform source of heat. The temperature differences at the base of the sample was controlled by the internal thermocouple. Four thermocouples (a, b, c, d), as shown in Figure 3-19, were inserted along the sample so as to observe the temperature variations at different distances within the sample. The four thermocouples were mounted on hypodermic probe needles (11) that give the possibility of pushing them to the centre of the sample. However, during the electrical conductivity testing, the holes of thermocouples were blocked by insulated plastic plugs so as not to affect the electrical measurements.

3.4.3.2 Hydraulic testing system components

The hydraulic testing system was run with two different arrangements; one built for composite soils with low clay content (soils of high permeability), and the second arrangement was used for composite soils of high clay content (soils of relatively low to medium permeability). The principles are same in both arrangements in that they use the constant head test as a method for measuring the hydraulic conductivity. The two arrangements for performing hydraulic conductivity tests in the new cell are briefly described below:

- **Arrangement for composite soils of high permeability:-** The first arrangement consists of three external components; de-airing water unit; constant level tank, and outflow rate measuring means. The de-airing unit was used in conjunction with a vacuum pump for providing aired-free water to the system. The constant level tank that contains aired water was connected to the cell inlet as shown in Figure 3.7.

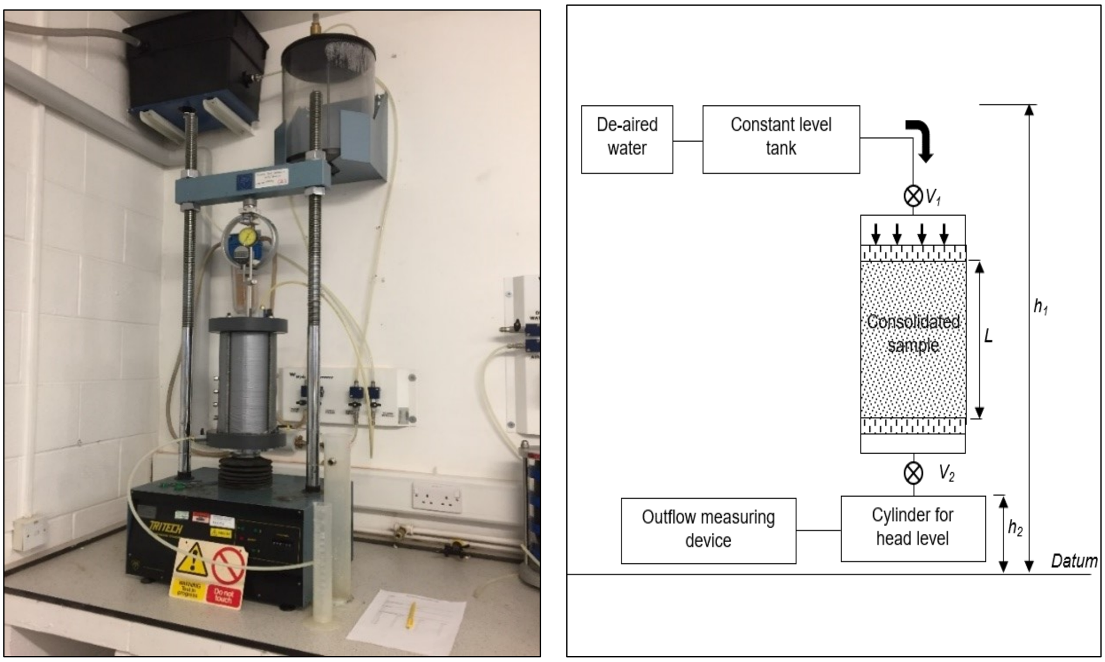


Figure 3.7: Arrangment for composite soils of high hydraulic coonductivity

To reach the condition of constant head method, the outlet from the soil sample was connected to a constant head cylinder with capacity of (1000 mL) containing overflow hole to another measuring smaller cylinder (250 mL). The level of outflow water in the bigger cylinder remains constant, and the rate of flow was taken from the reading of the small cylinder. This arrangement is similar to the one described in the British and ASTM standards.

- **Arrangement for composite soils of low to medium permeability:-** The arrangement here, consists of three external components; constant pressure system for applying pressure difference, volume change indicator for measuring the small rate of flow, and constant head cylinder, as shown in Figure 3.8. This type of hydraulic testing system is not covered by the British standard. However, the full description of this arrangement was described by Head (1982).

The constant pressure system was connected to the sample inlet from the top and the constant head cylinder was fitted to the base of the cell. A bladder air-water interface, Figure 3.8, was used along with the constant pressure unit allowing the inlet water to be well pressurised. This bladder cylinder can deliver pressurised water up to 1000 kPa. A digital gauge was fitted with the system to monitor the pressure. It is always better to incorporate the volume change indicator in the inflow pressure system because the water entering the sample is free of air, and so, this will provide more accurate readings.

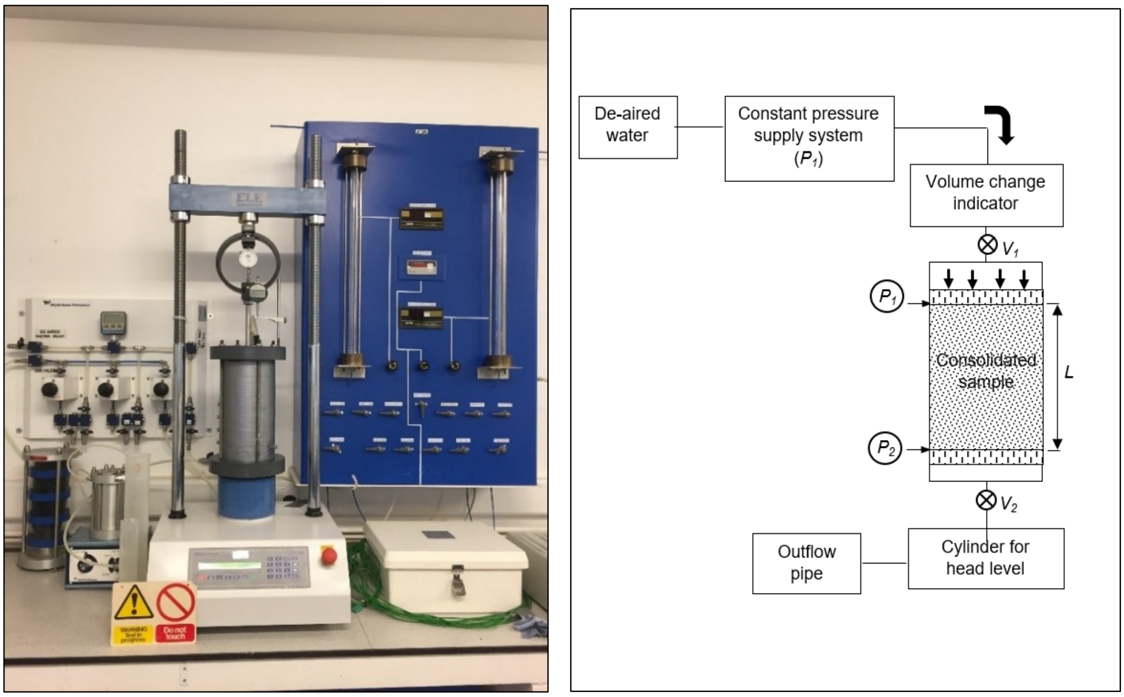


Figure 3.8: Arrangment for composite soils of low and medium hydraulic conductivity

3.4.3.3 Thermal testing system componstnts

The thermal testing system consists of five main components; cartridge heater element, temperature sensors, lab power supply, data logger with portable laptop. Details of the thermal testing system are shown in Figure 3.9 and a description of the components are described below:

- **Cartridge heater element**:- the cartridge heater was specially designed by Chromalox Company resident in the UK to supply the desired temperatures. It is mainly made of stainless steel with (Voltage = 240V, power = 300W).
- **Temperature sensors**:- thermocouples type *K*, supplied by *RS* Component Company in UK, were used as temperature sensors for measuring the temperature variations through a soil sample.
- **Lab power supply**:- A DC lab power device type TTi as shown in Figure 3.9, was used as a source of power for feeding the cartridge heater element and generating the required heat flow through a sample. This model can supply constant voltage/current up 150 V/4 A with fine and coarse control settings.

- **Data logger unit with potable laptop computer**:- The main purpose of the data logger unit was to read and record the output readings of the temperatures of the thermocouple sensors involved in thermal tests. After the test, the data logger unit could be connected directly to a laptop computer for taking out the temperature measurements.

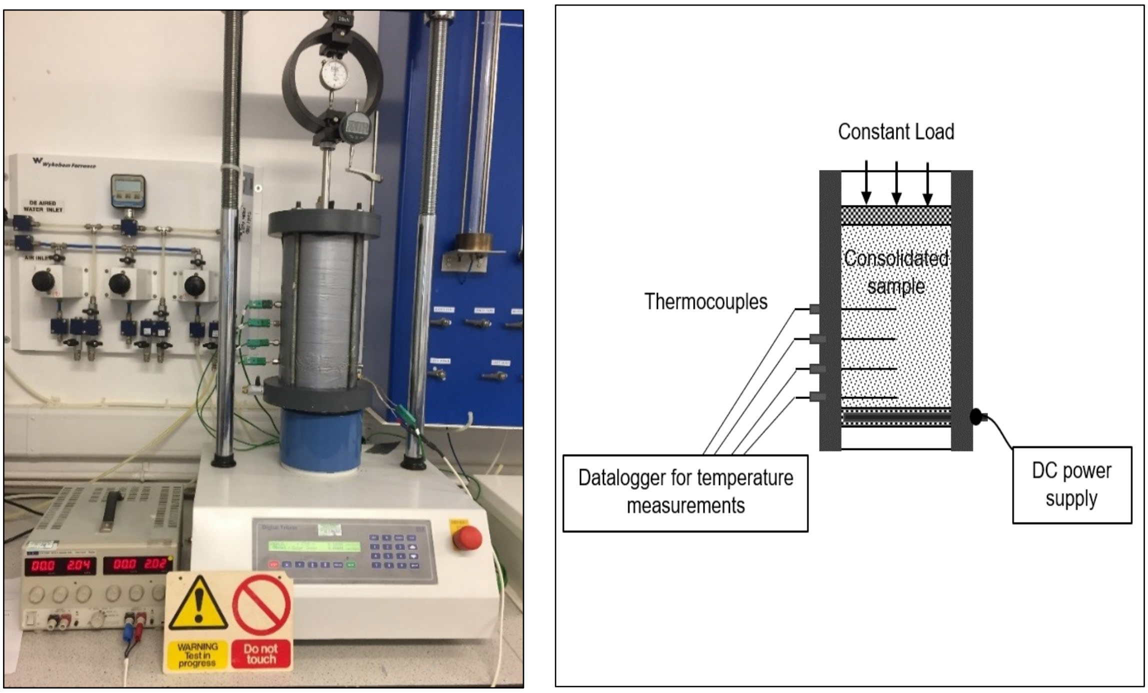


Figure 3.9: A photo and schematic digram of thermal conductivity meaurements

3.4.3.4 Electrical testing system components

The external components of the electrical testing system consisted of a lab power supply; multimeter device, as shown in Figure 3.10. The lab power supply unit was used for applying the desired voltage increments across the soil sample. The multimeter device was incorporated in the electric circuit for measuring the low value of flowing current.

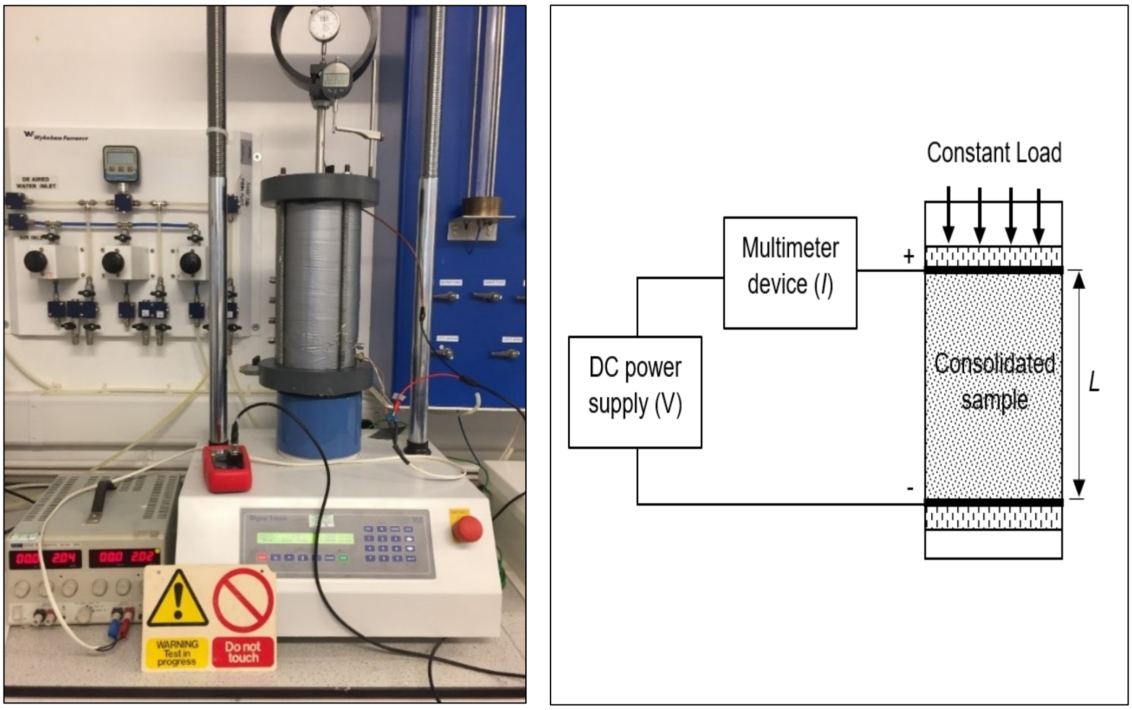


Figure 3.10: A photo and schematic digram of electrical conductivity meaurement

3.4.4 Test procedures for determination of soil' conductivities

In general, the test procedures involved in the determination of soil's conductivities include three stages; sample preparation and set up, consolidation, and conductivity measurements. The measurements of hydraulic and thermal conductivity were carried out on the same consolidated sample. However, this was only for one type of composite soils that is fine sand-kaolinite mixtures. For all other composite soil mixtures, hydraulic conductivity testing was not included.

The measurements of the electrical conductivity are expected to be more complicated due to the fact that flow of direct current in saturated soils can generate the phenomena of electro-osmosis which can eventually alter the internal structure of the soil, specifically for soils of high clay content. Thus, the soil sample for electrical conductivity was extruded and changed after each electrical test. In what follows, a full description of these measurements is provided.

3.4.4.1 Composite soil samples preparation and setup

A composite soil with varying coarse (clean sands) and fine (pure clays) grains was first mixed together as dry powder for about half hour using a motorised rotary mixer and then blended as a slurry using high water content for about quarter hour. The water content of 1.5 times of the liquid limit was used to ensure that they were fully saturated but sufficiently viscous to prevent segregation. Note that the liquid limit used here was based on the whole mixture and not only on the clay content in the mixture as stated by the British standard. The concept of the liquid limit being the point at which a soil begins to behave as a liquid was used to help achieve full saturation.

Prior to pouring the slurry-like mixture into the conductivity cell, the non-porous copper disc was thoroughly cleaned, and placed at the bottom of the cell. Following that, the threaded cartridge heater was pushed through the cell acrylic body to sit inside the copper disc. A perforated copper disc was placed above the non-porous copper disc to act as a drain in the consolidation and hydraulic conductivity test and as an electrode in the electrical conductivity measurement. A screen of filter paper was placed above the two-copper discs preventing finer grains from passing.

After greasing the internal faces of the cell, the slurry-like mixture was poured into the conductivity cell in layers up to the desired height. The cell was vibrated using a shaking table to eliminate any entrapped air and the cell sealed and stored overnight to ensure homogeneity of the soil. After pouring the slurry-like mixture in the cell, another screen of filter paper was placed above the sample. A loading cap attached to the perforated copper disc was placed on the filter paper. During this process, care was taken to avoid trapping air between the sample, filter paper, and perforated copper disc. In this stage, the initial conditions of the sample (i.e. diameter, height, and weight of the sample) were measured in order to use in the interpretation of the conductivity results.

3.4.4.2 Consolidation stage

The assembled cell was then centrally placed on the platform of the triaxial loading frame. The consolidation of the sample was measured using a dial gage (see Figure 3.7 & Figure 3.8) with a resolution of 0.001 mm. The dial gauge was adjusted for the zero reading, and 5 kPa stress was applied to the sample as a seating pressure by manually moving down the crosshead of the loading frame to rest on the loading column. The slurry-like sample was consolidated to the desired stress/density using a constant rate of strain. The rate of strain was selected depending on the type of the soil being tested and its permeability. Soils of low permeability would need less than 0.001 mm/min and 0.04 mm/min for high permeability soils. During the consolidation process, the outlet water was allowed to drain from both bottom and top of the sample using V_1 and V_2 valves. The consolidation was terminated when the soil sample reached the desired conditions in terms of void ratio and density. The load at which the consolidation was stopped was maintained while the conductivity tests were performed.

3.4.4.3 Hydraulic conductivity stage

As described in the section 3.4.3.2, two arrangements were built for the purpose of determining the coefficient of hydraulic conductivity of composite fine and coarse soils.

The testing procedures followed in the first arrangement that is for high permeability composite soils, were similar to those described in the British and ASTM standards for constant head test. Prior to the measurements, drainage lines and all the possible connections were checked, flushed with water and all valves were closed. The soil sample inside the conductivity cell had already consolidated to the required conditions (e.g. at a certain void ratio). The water was first de-aired using a de-airing system and run into the top of the constant levelling tank. The height of the tank was positioned at a suitable level above the cell so that it could provide the desired hydraulic gradient. The valves at the top and bottom of the cell (V_1 and V_2 in Figure 3.7) were opened to allow for water to flow down through a soil sample.

The levels of the water in the tank (h_1, mm) and in the big cylinder (h_2, mm) were adjusted to remain constant and the hydraulic gradient (i) across the sample was determined from the ratio of difference in heads ($\Delta h = h_1 - h_2$) to length of the sample (L, mm). Once the steady-state condition was achieved, the cumulative volume of water flowing (Q, mL) out of the big cylinder was collected in the small graduated cylinder at a suitable time interval (t, min) and then plotted. The slope of the relationship line represents the flow rate of water (q, mL/min). An example of a typical plot for the cumulative volume of water with time is shown in Figure 3.11 for a fine sand-kaolinite mixture with 20% kaolinite content (FSK20). The hydraulic conductivity (k_h) was determined using Darcy's law from:

$$k_h = \frac{q}{A * i * 60} \tag{3.3}$$

Where q is the rate of flow in (mL/min), A is the cross sectional area of the sample, i is the hydraulic gradient, and 60 was used for the purpose of unit conversation to obtain the hydraulic conductivity, k_h, in (m/s),

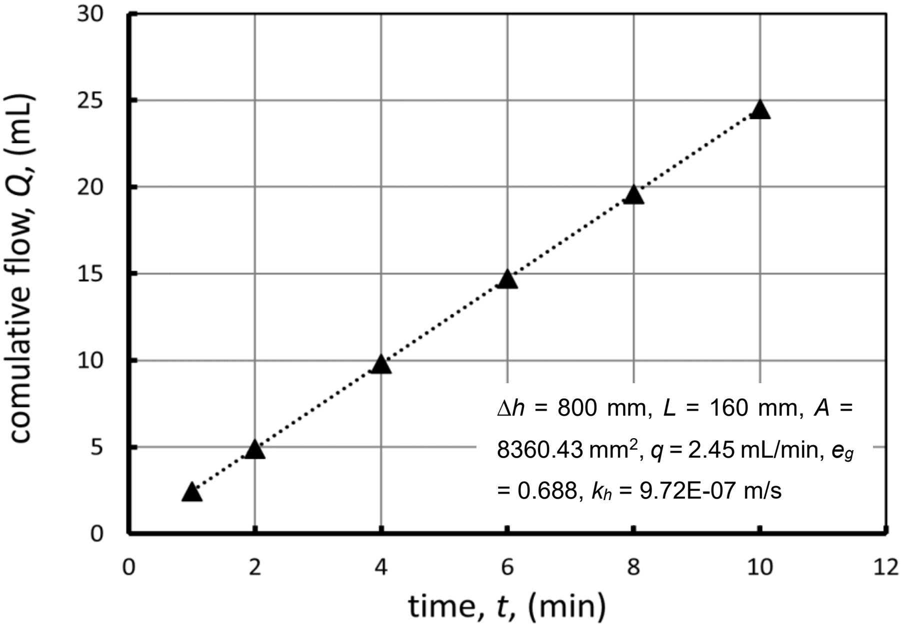


Figure 3.11: The typical graphical plot of the cumulative volume of water with time for fine sand-kaolinite mixture with kaolinite content of 20% (FSK20)

For composite soils of low and intermediate permeability, it is very difficult to induce the water to flow through the very small channels through the soil using the difference in gravitational potential. Therefore, in the second arrangement, the constant pressure unit was connected to the top of the cell instead of the constant level tank (see Figure 3.8) so that a wide range of potential difference could be applied. Also, to measure the small rate of flow, the volume change indicator was incorporated into the inlet line to the sample. The outlet line from the cell was connected to a big cylinder containing an overflow hole. As stated in section 3.4.3.2, this arrangement and testing procedures are not covered in the standards.

After checking all drainage and connections lines and filling them with de-aired water, the system was first pressurised while the valve on the cell top (V_1, Figure 3.8) was closed. The pressure applied was enough to produce a hydraulic gradient capable of initiating the flow of water through the sample (and within the recommended value in Table 2.2 in Chapter 2. Thus, the maximum inlet pressure used was 48 kPa. At this stage, the valves on the inlet (V_1) and outlet (V_2) lines of the cell were open to permit water to flow though the sample. The level of the outflow water inside the constant big cylinder was adjusted until it was constant and at the same level of the base of the sample so that the head in the outlet was (h_2 = zero). Once steady-state was achieved, the readings of water flow in the volume change unit were monitored and recorded at suitable time intervals.

If the inlet pressure (P_1) is to be used as an equivalent to the water head then:

$$h_1 = \frac{P_1}{\gamma_w} = \frac{P_1}{9.81} = 102P_1 \qquad (3.4)$$

where h_1 is the inlet water head in (mm), P_1 is the inlet pressure in (kPa), the hydraulic gradient (i) was then known from:

$$i = \frac{\Delta h}{L} = \frac{h_1 - h_2}{L} = \frac{102P_1 - zero}{L} \qquad (3.5)$$

And the hydraulic conductivity (k_h) was then determined based on equ. (3.3). A typical graph of the water flow vs time used in the calculation of k_h in pure kaolinite is shown in Figure 3.12.

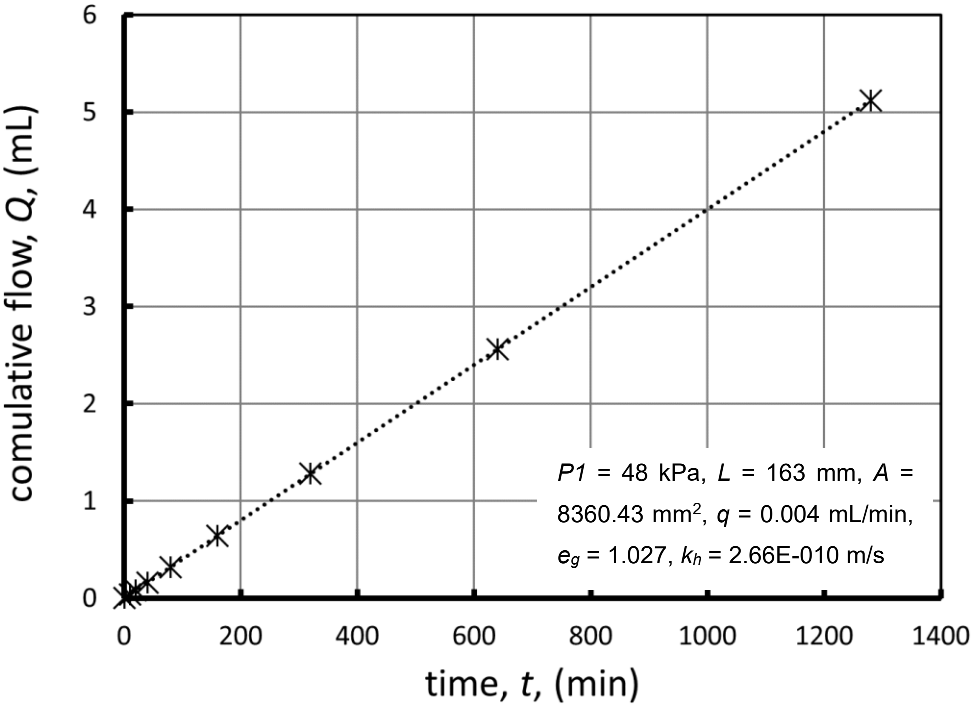


Figure 3.12: The typical graphical plot of the volume of water vs time for pure kaolinite (FSK100)

3.4.4.4 Thermal conductivity stage

In the thermal conductivity measurements, the output terminals of the cartridge heater were connected to the lab power supply to generate the desired temperature difference. Four thermal sensors (thermocouples type K) with a length of 100 mm and a diameter of 3 mm were pushed into the consolidated soil sample to the centre. These four thermocouples were connected to the data logger for recording the variation of temperatures across the soil sample. The full setup of the cell for thermal conductivity measurement is shown more clearly in Figure 3.9.

After setting up all the necessary connections, the sample was left until the sample and room temperature were the same, and the sample, at this point, was ready for thermal testing. The power was switched on to supply an appropriate energy to the cartridge heater and generate the desired temperature at the bottom of the sample. The top of the sample was already, in the hydraulic conductivity tests, filled with de-aired water at a constant temperature near to the ambient. The external radial faces of the sample were insulated with very low thermal conductivity materials; acyclic with (k_t = 0.2 W/m °C) surrounded by polyethylene foam with (k_t = 0.038 W/m °C) with a thickness of 40 mm, as shown in Figure 3.13, in order to reduce the undesired radial heat loss to a minimum. Further, at the sample base, another polyethylene foam insulation was put to minimize the basal heat loss. These all were to allow for the application of Fourier's law to be applicable.

Figure 3.13: Top view of the conductivity cell body showing the external insulation

For all thermal conductivity tests, the power supplied was selected so that it could provide the required temperature gradient which did not exceed the allowable temperature limit of the cell body acrylic (62 °C). Therefore, a constant power of (Q = 30.2 V * 0.12 Amp = 3.624 W) was used to operate the cartridge heater to create the thermal gradient through the samples.

The temperatures of the inserted thermocouples at different locations at 0, 10, 50, and 90 mm distances from the heater source along the sample were monitored regularly until the steady state condition was established (normally after 48 hr). At this stage, the power was turned off to allow the sample to cool down to the room temperature. All temperature readings at the four locations, schematically shown in Figure 3.14, were measured and recorded using the data logger unit and then transferred to the laptop computer for the analysis process. An example of a typical temperature-time profile is shown in Figure 3.15 for kaolinite at porosity, n = 0.426.

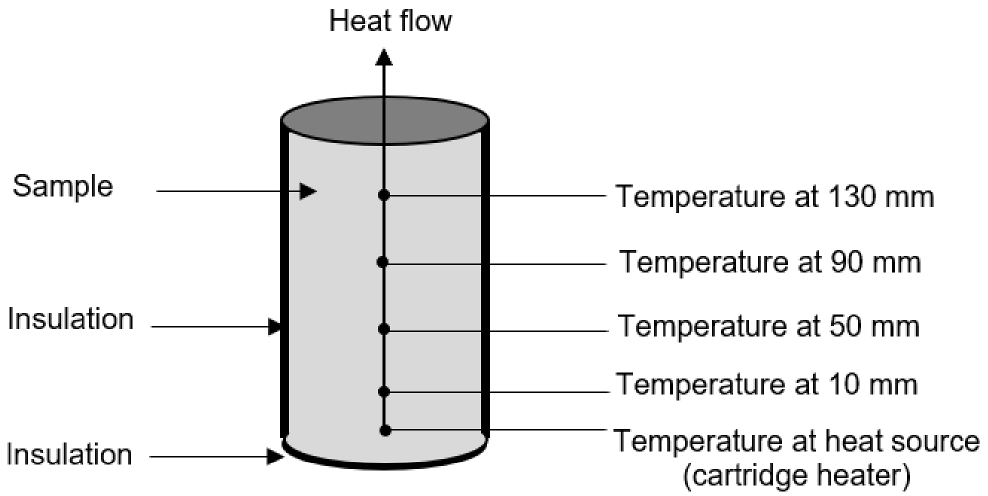


Figure 3.14: The locations at which the temperature measurements were recorded

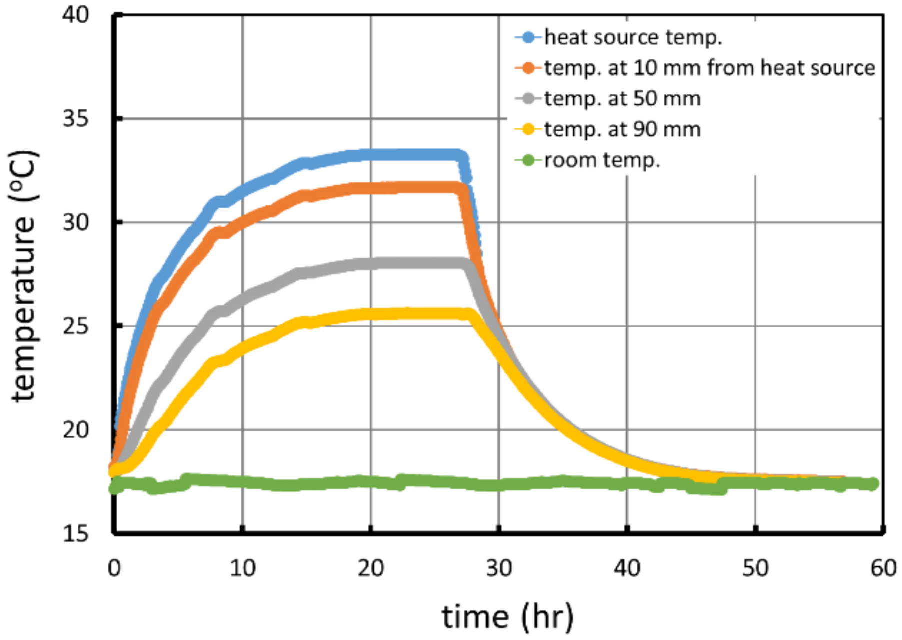


Figure 3.15: Typical profile of temperature vs time of saturated kaolinite (FSK100) at porosity of 0.426

Typically, and based on Fourier's law, the temperature difference between any two points at the steady-state condition can be used to calculate the thermal conductivity using equ. (3.2). However, Fourier assumes that heat flux between the two points is constant in that there is no radial heat loss. To assess the radial heat loss and to determine the correct thermal conductivity value in the new cell, three values of the thermal conductivity were calculated based on three temperature differences using the four temperature measurements at (0, 10, 50, and 90 mm). The first thermal conductivity was based on the temperatures at 0 mm and 10 mm with distance from the heater (L = 10 mm), the second, the temperature readings at 0 mm and 50 mm (L = 50 mm), and the third using temperatures at 0 mm and 90 mm (L = 90 mm). The three values of the thermal conductivity were plotted with response to their corresponding distances from the heating source. An example is shown in Figure 3.16 for pure kaolinite at porosity (n = 0.426). The assessment of the radial heat loss was based on the slope of the best fit line in Figure 3.16. The sloping line confirms that the conductivity cell exhibits an amount of heat loss along the sample. Therefore, the thermal conductivity of the sample had to be corrected.

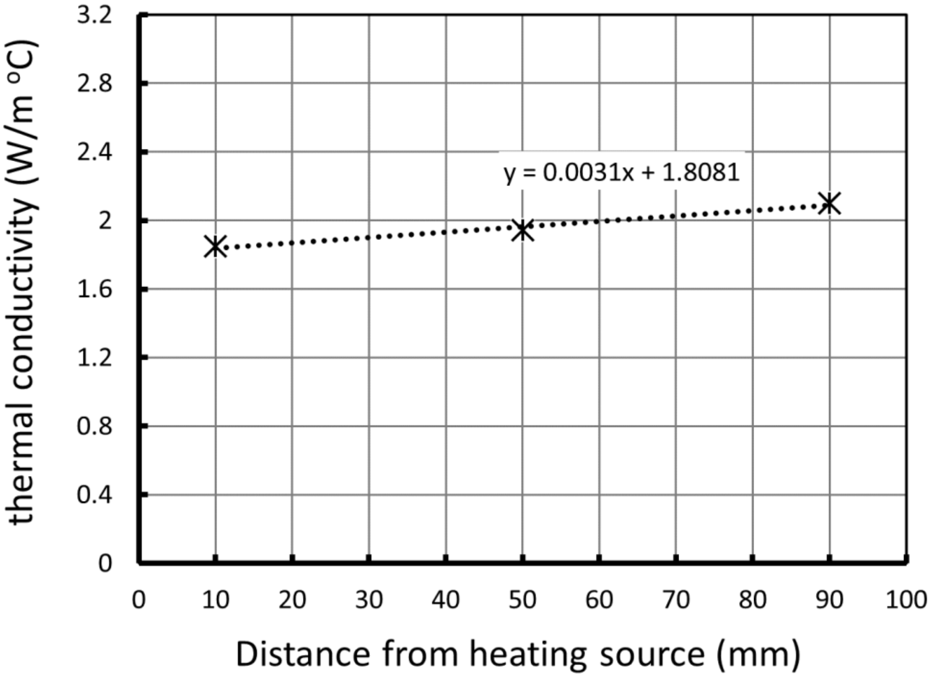


Figure 3.16: An example of the determination of the corrected thermal conductivity for pure kaolinite (FSK100) at n = 0.426

The ideal corrected thermal conductivity is the value at 0 distance from the heater source in which there is no heat loss, which can be extrapolated from Figure 3.16 using the best-fit line equation at x = 0. In Figure 3.16, the corrected thermal conductivity for kaolinite is equal to 1.808 W/m.°C. These procedures for determination of the thermal conductivity was used by Alrtimi et al. (2014).

3.4.4.5 Electrical conductivity stage

Prior to the electrical conductivity measurements, the holes of the thermocouples were closed using insulated plastic plugs to avoid any effect on the current flow. The test procedures followed for the electrical conductivity measurements are somewhat similar to those that are described in the British standard (BS 1377-3:1990).

When electrical conductivity was to be taken, the terminals on the two perforated copper electrodes (10, 15 in Figure 3.6) that are in a very good contact with the consolidated sample, were connected to the constant power supply using copper wires. Incremental voltages up to 15 voltages, were applied across the electrodes and the resulting current through the circuit was measured. The low ranges of current was measured using a multimeter device incorporated into the electrical circuit. Values of voltage, *V*, in Volts, were plotted against the readings of the corresponding current, *I*, in Ampere. An example for the typical voltage-current plot is presented in Figure 3.17 for pure saturated kaolinite clay.

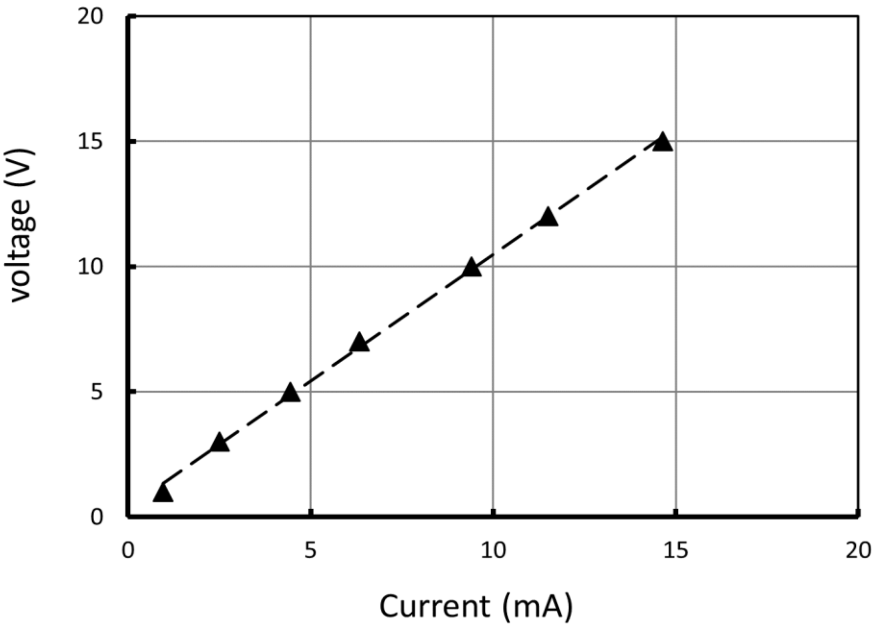


Figure 3.17: Voltage-current plot for saturated kaolinite clay (FSK100).

The slope of the correlated line in Figure 3.17, represents the soil resistance, *R*, in Ohm which was determined from:

$$R = \frac{\Delta V}{\Delta I} \qquad (3.7)$$

The resistivity, r_s, in Ohm.m, was then determined by:

$$r_s = \frac{RA}{1000L} \qquad (3.8)$$

Where A is the cross-sectional area of the soil sample (mm^2), and L is the sample length between the two electrodes (mm). The electrical conductivity, σ_T, in 1/Ohm.m; mho/m or S/m, was then calculated from the inverse of the resistivity, r_s, by :

$$\sigma_T = {}^1/_{r_s} \qquad (3.9)$$

Throughout the conductivity system tests, all measurements recorded were stable and conformed to Ohm's law. Note that, the time to perform the electrical test was insufficient to generate the electro-kinetic phenomena (specifically electroosmosis process) which would have led to further loss of water that may affect the measurements.

3.5 Summary

The details of the main materials (sands and clays) used to form the composite soil mixtures and their index properties were presented. For the purposes of testing these materials, two new pieces of laboratory equipment were designed. The first equipment was built to comply with the assumption of Terzaghi principle of one-dimensional consolidation to determine the hydraulic conductivity based on the consolidation theory. The second one was designed and developed to allow for measuring all soil's conductivities; hydraulic, thermal and electrical conductivity based on the application of Darcy, Fourier, and Ohm for one-dimensional flow.

A full detailed description of the two equipment, their criteria and principles, and the test methods used to measure soil conductivities was provided. It was found that such equipment is simple, effective and provided repeatable results which could be compared to data obtained from other laboratory investigations and published models.

The results of the hydraulic, thermal and electrical conductivity of a range of composite soil mixtures using the two designed equipment are shown in chapters four, five and sex.

Chapter 4

Hydraulic Conductivity Results of Composite Soils

4.1 Introduction

This chapter presents the results of the tests to determine hydraulic conductivity of composite soils. Test results for consolidation were firstly interpreted, presented, and then used to determine the hydraulic conductivity indirectly. The behaviour of clay-dominated and sand-dominated composite soils and the transition between them during consolidation and hydraulic conductivity, and the factors that affect it are discussed. Empirical models to predict the coefficients of consolidation and hydraulic conductivity for composite soils were established.

Test results for the direct hydraulic conductivity measurements using the new designed conductivity cell are also presented. A comparison between the results of directly and indirectly determined values of coefficient of hydraulic conductivity is then made.

4.2 Composite soils used for direct and indirect hydraulic conductivity determinations

Six groups of composite soil mixtures were used for consolidation and indirect hydraulic conductivity determinations. A summary of these mixtures is presented in Table 4.1. For direct measurements of hydraulic conductivity, only one group of the mixtures was used in tests, which is group 1 in Table 4.1.

The classification properties of the composite soil mixtures illustrated in Table 4.1 were determined following procedures described in BS EN ISO 17892-12:2018 and BS 1377-2:1990. The consistency limits, liquid and plastic limits, for the composite soils were measured based on the whole sample rather than particles smaller than 425µm; that is the test was used as a proxy for strength. The liquid limit was measured using procedures of cone penetration method.

Table 4.1: The classification properties of composite soil mixtures

Groups	Mixtures	Symbol	Clay content (C_m%)	Sand content (S_m%)	Specific gravity (G_T)	Liquid limit (I_L %)	Plastic limit (I_P %)	Plasticity index (*PI* %)	Clay fraction < *2μm*	Activity (*A*)	Maximum void ratio (e_{max})
1	Kaolinite	FSK100	100	0	2.60	56.0	33.0	23.0	34.0	0.68	2.30
	Fine sand - Kaolinite	FSK90	90	10	2.60	52.1	30.9	21.2	30.6	0.69	
	Fine sand - Kaolinite	FSK80	80	20	2.60	48.2	28.8	19.4	27.2	0.71	
	Fine sand - Kaolinite	FSK70	70	30	2.61	43.4	26.0	17.4	23.8	0.73	
	Fine sand - Kaolinite	FSK60	60	40	2.61	38.7	23.0	15.7	20.4	0.77	
	Fine sand - Kaolinite	FSK50	50	50	2.62	33.2	19.3	13.9	17.0	0.81	
	Fine sand - Kaolinite	FSK40	40	60	2.62	27.9	15.4	12.5	14.8	0.84	
	Fine sand - Kaolinite	FSK30	30	70	2.62	22.9	12.9	10.0	10.3	0.97	
	Fine sand - Kaolinite	FSK20	20	80	2.63	17.9	-	-		-	
	Fine sand - Kaolinite	FSK10	10	90	2.63	13.2	-	-		-	
	Fine sand	FS	0	100	2.63	-	-	-		-	1.14
2	Medium sand - Kaolinite	MSK90	90	10	2.60	51.6	31.2	20.4	30.6	0.66	
	Medium sand - Kaolinite	MSK80	80	20	2.61	47.3	28.6	18.7	27.2	0.68	
	Medium sand - Kaolinite	MSK70	70	30	2.61	42.6	25.7	16.9	23.8	0.71	
	Medium sand - Kaolinite	MSK60	60	40	2.62	37.8	22.7	15.1	20.4	0.74	
	Medium sand - Kaolinite	MSK50	50	50	2.62	32.2	19.2	13.0	17.0	0.76	
	Medium sand - Kaolinite	MSK40	40	60	2.62	26.9	15.2	11.7	14.8	0.79	
	Medium sand - Kaolinite	MSK30	30	70	2.63	21.6	11.0	10.6	10.2	0.78	
	Medium sand - Kaolinite	MSK20	20	80	2.63	16.9	-	-	-	-	
	Medium sand - Kaolinite	MSK10	10	90	2.64	11.8	-	-	-	-	
	Medium sand	MS	0	100	2.64	-	-	-	-	-	1.11
3	Bentonite	FSB100	100	0	2.55	105.0	48.0	57.0	29.0	1.97	3.30
	Fine sand - Bentonite	FSB90	90	10	2.55	97.1	45.2	51.9	26.0	1.99	
	Fine sand - Bentonite	FSB80	80	20	2.56	87.9	40.7	48.3	24.0	2.01	
	Fine sand - Bentonite	FSB70	70	30	2.57	78.1	35.5	42.6	21.0	2.03	
	Fine sand - Bentonite	FSB60	60	40	2.58	67.5	29.6	37.4	18.0	2.08	
	Fine sand - Bentonite	FSB50	50	50	2.59	58.2	26.8	31.4	15.0	2.09	
	Fine sand - Bentonite	FSB40	40	60	2.60	47.3	21.8	25.5	12.0	2.13	
	Fine sand - Bentonite	FSB30	30	70	2.61	36.9	17.7	19.2	9.0	2.13	
	Fine sand - Bentonite	FSB20	20	80	2.62	27.0	-	-	-	-	
	Fine sand - Bentonite	FSB10	10	90	2.63	16.6	-	-	-	-	
4	Medium sand - Bentonite	MSB90	90	10	2.56	95.0	46.0	52.0	26.0	2.00	
	Medium sand - Bentonite	MSB80	80	20	2.58	85.8	41.1	47.1	24.0	1.96	
	Medium sand - Bentonite	MSB70	70	30	2.59	76.5	35.3	41.3	21.0	1.97	
	Medium sand - Bentonite	MSB60	60	40	2.60	65.7	29.1	36.2	18.0	2.01	
	Medium sand - Bentonite	MSB50	50	50	2.60	56.0	26.0	30.0	15.0	2.00	
	Medium sand - Bentonite	MSB40	40	60	2.61	45.3	21.4	23.9	12.0	1.99	
	Medium sand - Bentonite	MSB30	30	70	2.61	35.4	17.3	18.1	9.0	2.01	
	Medium sand - Bentonite	MSB20	20	80	2.63	26.1	-	-	-	-	
	Medium sand - Bentonite	MSB10	10	90	2.64	15.0	-	-	-	-	
5	Illlite	FSI100	100	0	2.67	37.6	20.0	17.6	42.9	0.41	1.22
	Fine sand – Illite	FSI90	90	10	2.67	34.5	18.1	16.4	38.1	0.43	
	Fine sand – Illite	FSI80	80	20	2.66	31.5	16.2	15.3	34.8	0.44	
	Fine sand – Illite	FSI70	70	30	2.66	28.8	14.3	14.5	31.5	0.46	
	Fine sand – Illite	FSI60	60	40	2.65	26.0	13.1	12.9	26.0	0.48	
	Fine sand – Illite	FSI50	50	50	2.65	23.3	11.6	11.7	21.9	0.50	
	Fine sand – Illite	FSI40	40	60	2.64	20.5	-	-	-	-	
	Fine sand – Illite	FSI30	30	70	2.64	18.0	-	-	-	-	
	Fine sand – Illite	FSI20	20	80	2.63	15.2	-	-	-	-	
	Fine sand – Illite	FSI10	10	90	2.63	11.7	-	-	-	-	
6	Sepiolite	MSSP10	100	0	2.30	118.0	86.5	31.5	27.0	1.17	2.52
	Medium sand - Sepiolite	MSSP90	90	10	2.34	104.9	77.5	27.4	23.4	1.17	
	Medium sand - Sepiolite	MSSP80	80	20	2.38	92.9	69.0	23.9	20.1	1.19	
	Medium sand - Sepiolite	MSSP70	70	30	2.42	81.5	59.7	21.8	18.0	1.21	
	Medium sand - Sepiolite	MSSP60	60	40	2.46	70.0	51.2	18.8	15.3	1.23	
	Medium sand - Sepiolite	MSSP50	50	50	2.50	58.5	43.0	15.5	12.5	1.24	
	Medium sand - Sepiolite	MSSP40	40	60	2.54	48.0	35.5	12.5	10.0	1.25	
	Medium sand - Sepiolite	MSSP30	30	70	2.57	36.5	27.0	9.5	7.5	1.26	
	Medium sand - Sepiolite	MSSP20	20	80	2.61	25.1	-	-	-	-	
	Medium sand - Sepiolite	MSSP10	10	90	2.64	14.2	-	-	-	-	

The data of the consistency limits shows that when the sand content increases, both liquid and plastic limits decrease (Figure 4.1). The relationship between sand content and consistency limits is linear for all composite soils up to 70% sand content (except for fine sand-illite mixtures which does not have data above 40% sand content). At a certain sand content, the order for consistency limits is sepiolite, bentonite, kaolinite, and illite. Figure 4.1 suggests that the consistency limits of the composite soil mixtures are totally controlled by the content and mineralogy of both clay and sand in the mixtures.

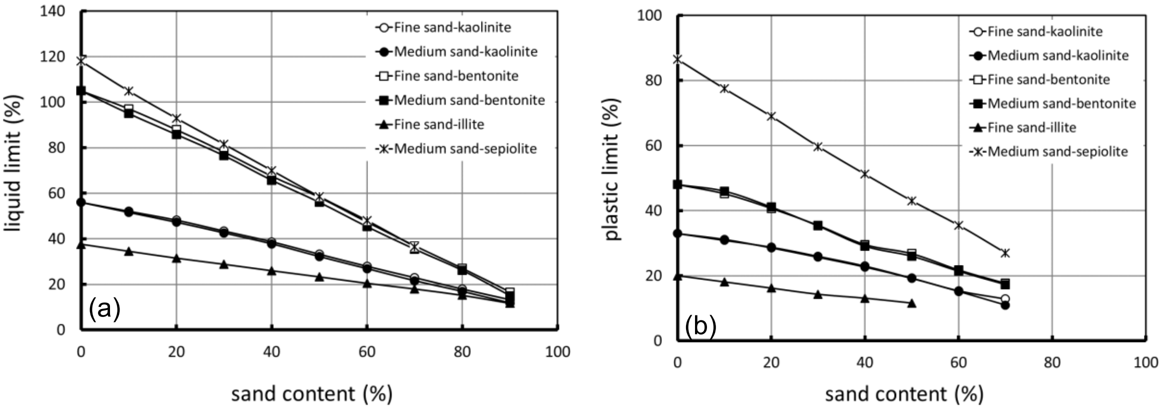


Figure 4.1: Effect of sand content on (a) liquid limit, (b) plastic limit of composite soils

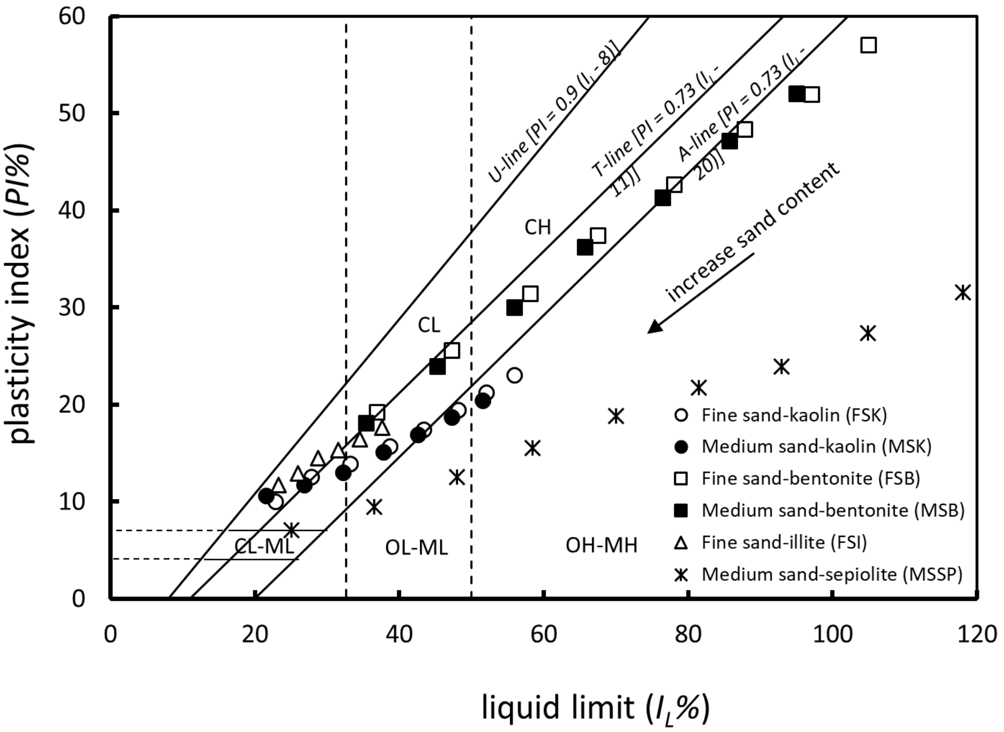


Figure 4.2: The plasticity chart for the composite soils

The plasticity chart of all composite soil mixtures, illustrated in Figure 4.2, comprises the T-line (Boulton and Paul, 1976), a line around which the limits of composite glacial soils tend to cluster. The data of the composite soils tends to move towards the T-line as the sand content increases. The particle size distribution of the composite soils, shown in Figure 4.3, was established from gathering the data of sieve analysis and hydrometer tests for each composite soil group using the concept described in Das (2002).

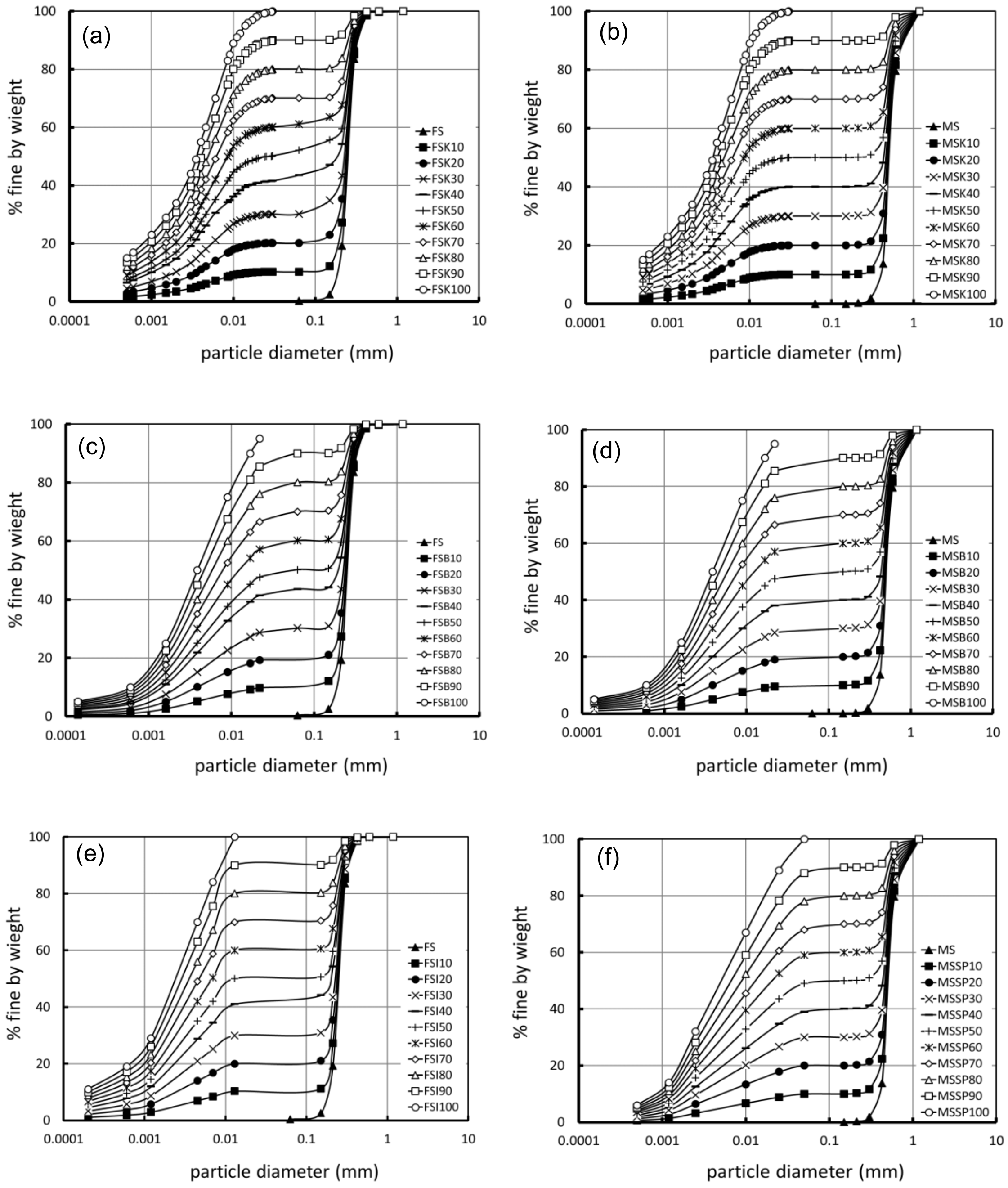


Figure 4.3: The particle size distribution for (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; and (f) medium sand-sepiolite mixtures

Note that the clay content, column 4 in Table 4.1, is different from clay-particle content % < 2µm, column 10 in the Table 4.1, which is used in the calculation of soil's activity. The clay content represents the amount of clays by weight added to the composite soil mixture and, hence, it automatically includes particles finer than 2µm.

The activity (*A*) of all soil mixtures was determined using the concept of Skempton (1953) using the plasticity index ($PI = I_L - I_P$) and % clay finer than 2µm. It should be noted that the activity of any specific type of composite soil mixture in the Table 4.1, has a very small variation with increasing sand content. This can be attributed to an increase in the sand content results in nearly an equal decrease in both the plasticity index (*PI*) and % clay less than 2mu. This is consistent with the Seed et al. (1964) observation who assessed the plasticity properties of several artificially prepared mixtures of sand and processed clay to conclude that although the slope of the plasticity index (*PI*) versus clay particles finer than 2µm is linear, the line does not always pass through the origin and the variation in the activity for a specific type of sand-clay mixture is small.

4.3 Hydraulic conductivity results of composite soils

The coefficient of hydraulic conductivity, k_h, was determined indirectly from the consolidation tests using the new consolidation cells, and directly using the new conductivity cells with the principles of constant head method. Sixty one samples of composite soils with varying sand-clay types and contents were tested under one-dimensional consolidation process to determine their hydraulic conductivity.

For the direct hydraulic experiments, only one type of composite soils was used (fine sand-kaolinite mixture, group 1 in Table 4.1). In what follows, the results obtained from consolidation-indirect and direct measurements are presented.

4.3.1 Indirect hydraulic conductivity from consolidation tests

4.3.1.1 Consolidation behaviour of composite soils

The data from consolidation tests were plotted in terms of global void ratio (e_g) against vertical effective stress on a semi-log scale for the different mixtures of composite soils (Figure 4.4). This figure indicates that the consolidation characteristics are a function of the confining stress, particle size distribution and clay mineralogy. The shape of the curves is seen slightly concave upward for all composite soil mixtures except for composite soils with bentonite and sepiolite, which show that the consolidation curves are an inverse *S* shape which is uncommon in reconstituted soils (Hong et al., 2010). According to Burland (1990), the consolidation curves of reconstituted clays at an initial water content of 1 - 1.5 times the liquid limit are in a shape somewhat concave upwards for the stress greater than 10 kPa. A similar conclusion was reported by Hong (2007) who carried out investigations on reconstituted Ariake clays. However, Hong and Cui (2010) showed an inverse S shape for consolidation curves of some reconstituted clays (Lianyungang, Baimahu, and Kemen clay) prepared at an initial water content of 1-2 times the liquid limit. This can be attributed to the initial vertical stresses that were used, are less than those at the transition point from an overconsolidated soil to a normally consolidated soil. Hong and Cui (2010) investigated this further to show that the inflection in consolidation curve occurs because of the resistance deformation induced by suction stress, the stress at which the inflection occurs.

The variation of dry density with the sand content is shown in Figure 4.5. This figure shows that the density varies with the particle size distribution, clay/sand mineralogy and confining stress. It also shows, that as the sand content decreases and the confining stress increases; there is an increase in density to a maximum which then reduces to a value less than that of the sandy soil. This is probably because, initially, fine particles of clays replace the water in the voids between the coarser particles of sand (water-fines replacement), thus increasing the density but have little effect on the compression characteristics, which are a function of the packing of the coarse grains. At some point, where the large coarse particles are pushed apart and replaced by clay grains (coarse-fines replacement), the clay grains start to influence the compression of the soil, and the density reduces for a given pressure.

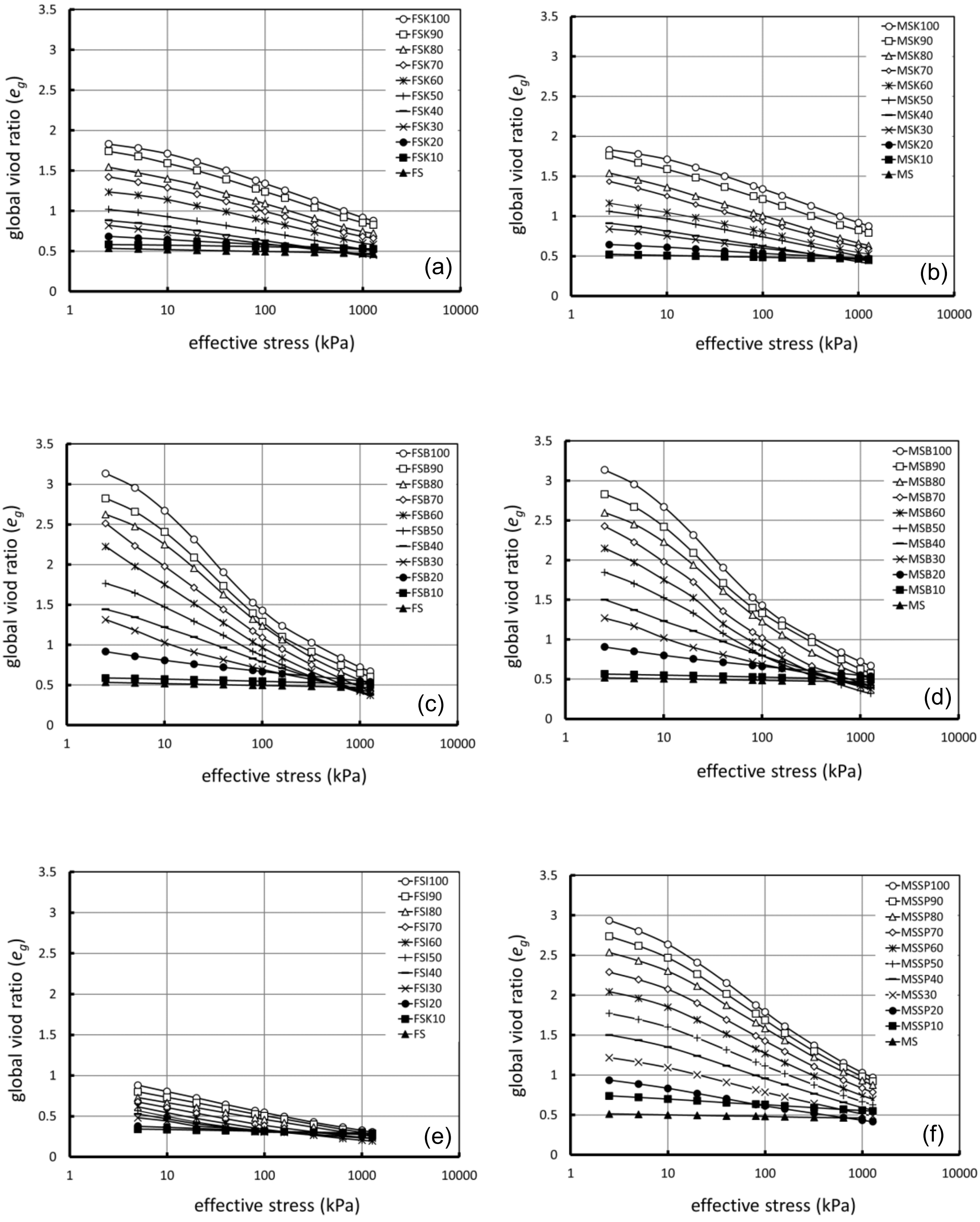


Figure 4.4: The variation of global void ratio (eg) with log effective stress for (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; and (f) medium sand-sepiolite mixtures

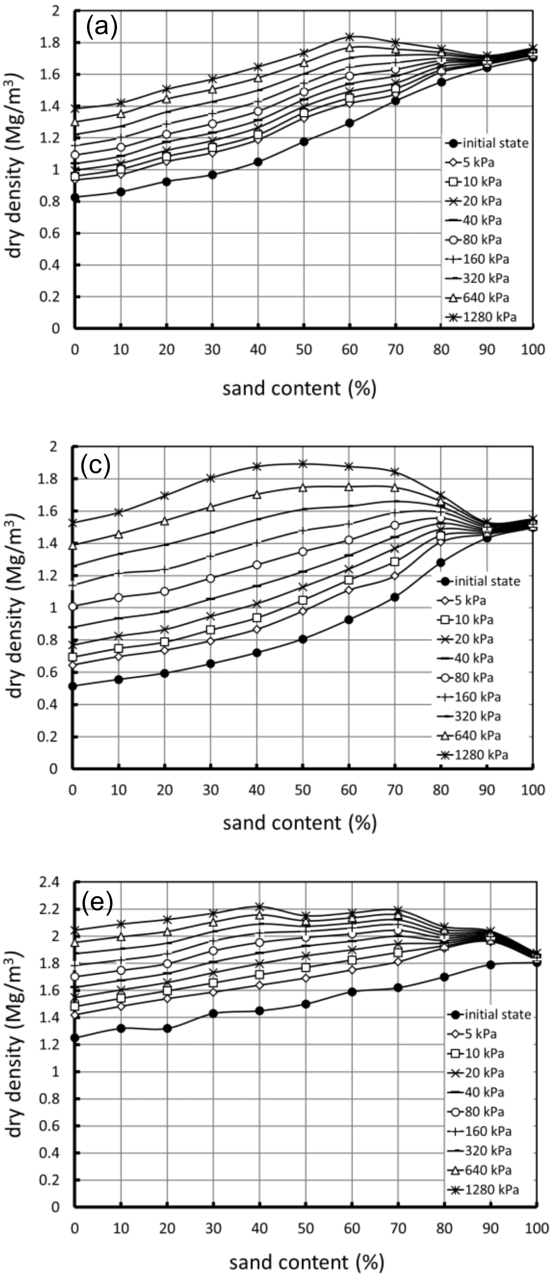


Figure 4.5: The variation of dry density with sand content for (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; and (f) medium sand-sepiolite mixtures

The transition from a clast (coarse) dominated to a matrix (fine) dominated soil appears, from the density plot, to occur when the clay content exceeds 10%; that is the sand content is less than 90%, expect for sepiolite for which the transition starts when 5% clay exists. To assess the transition in composite soil behaviour more clearly, it is better to use the matrix void ratio (e_m) and the intergranular void ratio (e_i) that can be calculated based on the global void ratio (e_g) and clay content (C_m) from equ. 2.3 & 2.5.

A composite soil will have the characteristics of a clast dominated soil under the consolidation process if the intergranular void ratio (e_i) is less than the maximum void ratio of the present sand (e_{max-s}) since the sand particles will be in contact with each other. If $e_i > e_{max-s}$, a composite soil will behave as a matrix, or clay- dominated soil. However, the switch from clast to matrix dominated behaviour is not so clearly defined. If the finer clay grains are added to coarse sand soils, they will, initially be held in suspension in the pore fluid or adhere to the coarse particles; i.e. they will have little effect on the compression characteristics. At some point, the fine grains will start to have an impact. Conceptually, this could occur when the fine grained content reaches its maximum void ratio, e_{max-f}. Note that the definition of e_{max-s} and e_{max-f} has been given in Chapter two, 2.3 which were measured here following ASTM D4254- 16.

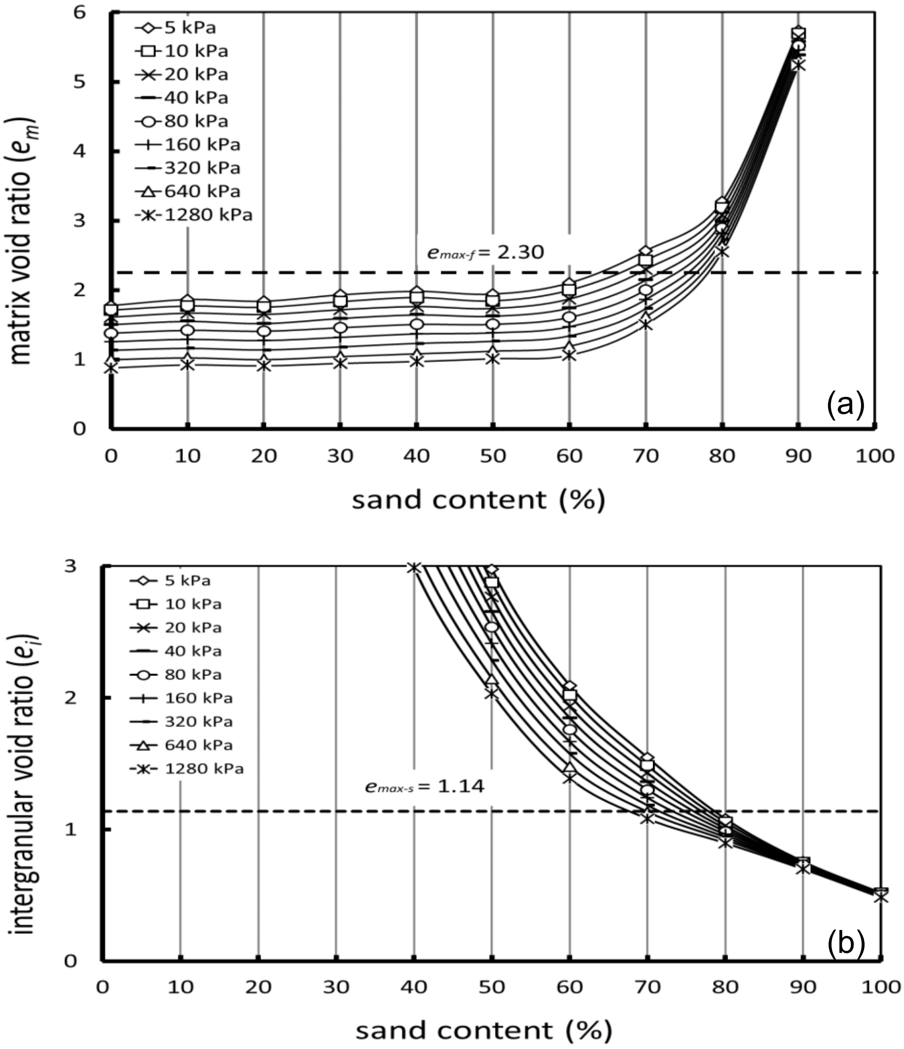


Figure 4.6: An example of the limits to the transition zone for fine sand-kaolinite showing the relationship between (a) the matrix void ratio, e_m, and the maximum void ratio for kaolin, e_{max-f}, and (b) the intergranular void ratio, e_i, and the maximum void ratio for sand, e_{max-s}, for different confining stresses

Thus, the transition zone could be defined by these two limits, the maximum void ratios (e_{max-f} and e_{max-s}) with the sand content at e_{max-f} being the upper limit. This is only the case, Table 4.2, if the confining stress exceeds 80kPa (40kPa in the case of sepiolite). At low confining effective stresses, the sand content at e_{max-s} exceeds that at e_{max-f}. Thus, as shown in Figure 4.6, the limits are affected by the confining stress and sand content. Inspection of Figure 4.5 shows that, if the confining stress exceeds 80kPa, the dry density increases as the fines content increases until it reaches a maximum. These tests suggest that there is a transition zone with two boundaries (58% to 85% sand content), which depends on the confining stress, sand and clay mineralogy and particle size distribution.

Table 4.2: The transition zone limits in all composite soil mixtures under consolidation processes

Stress (kPa)	% sand content											
	FSK		MSK		FSB		MSB		MSSP		FSI	
	e_{max-s}	e_{max-f}	e_{max-s}	e_{max-f}	e_{max-s}	e_{max-f}	e_{max-s}	e_{max-f}	e_{max-s}	e_{max-f}	e_{max-s}	e_{max-f}
5	79	65.1	79.3	62	83.2	60	83	58	85.1	60.4	75	54
10	78	66	77.8	65.4	82.2	72	82.2	68.1	84.6	65	73	60
20	77	69.2	77	68	81.5	76	82	76	82.8	68	70.2	66
40	76	71.6	76	72	80.5	78	80.9	78.4	80.7	72	69	70
80	74.5	74	74.8	74.8	79.2	79.4	80	80	77.7	75.8	66	74
160	73.3	75.1	74	77	77	80.3	78	81	74.4	78	62.3	75.8
320	71.8	76.4	72.2	77.2	74.5	81.5	75	82	70.9	80	61	77
640	70.3	77.3	70	77.9	71.2	82.2	70	82.9	66.2	81	60	78
1280	67.8	78	68.1	79	66.1	83	67	81.2	62	82	58	79

4.3.1.2 Consolidation characteristics

A review of Figure 4.4 and Figure 4.5 suggests that the consolidation behaviour of composite soils will be dominated by the clay if its content exceeds 15% to 42% by weight; that is the matrix void ratio (e_m) would be a better parameter than the global void ratio to characterise a matrix dominated composite soil.

The data in Figure 4.4 are replotted in terms of the matrix void ratio (e_m) in Figure 4.7 to show that the relationship between e_m and log σ_v' is more linear than that between e_g and log σ_v' for all composite soils, which suggests that, for a normally consolidated matrix or clay dominated soil, a linear trend can be assumed between e_m and log σ_v' for the purposes of establishing semi empirical correlations for compression characteristics. It is also noted that the consolidation lines converge to that of pure clays as the clay content increases with the lines following a similar trend if the fine- grained content exceeds 20%.

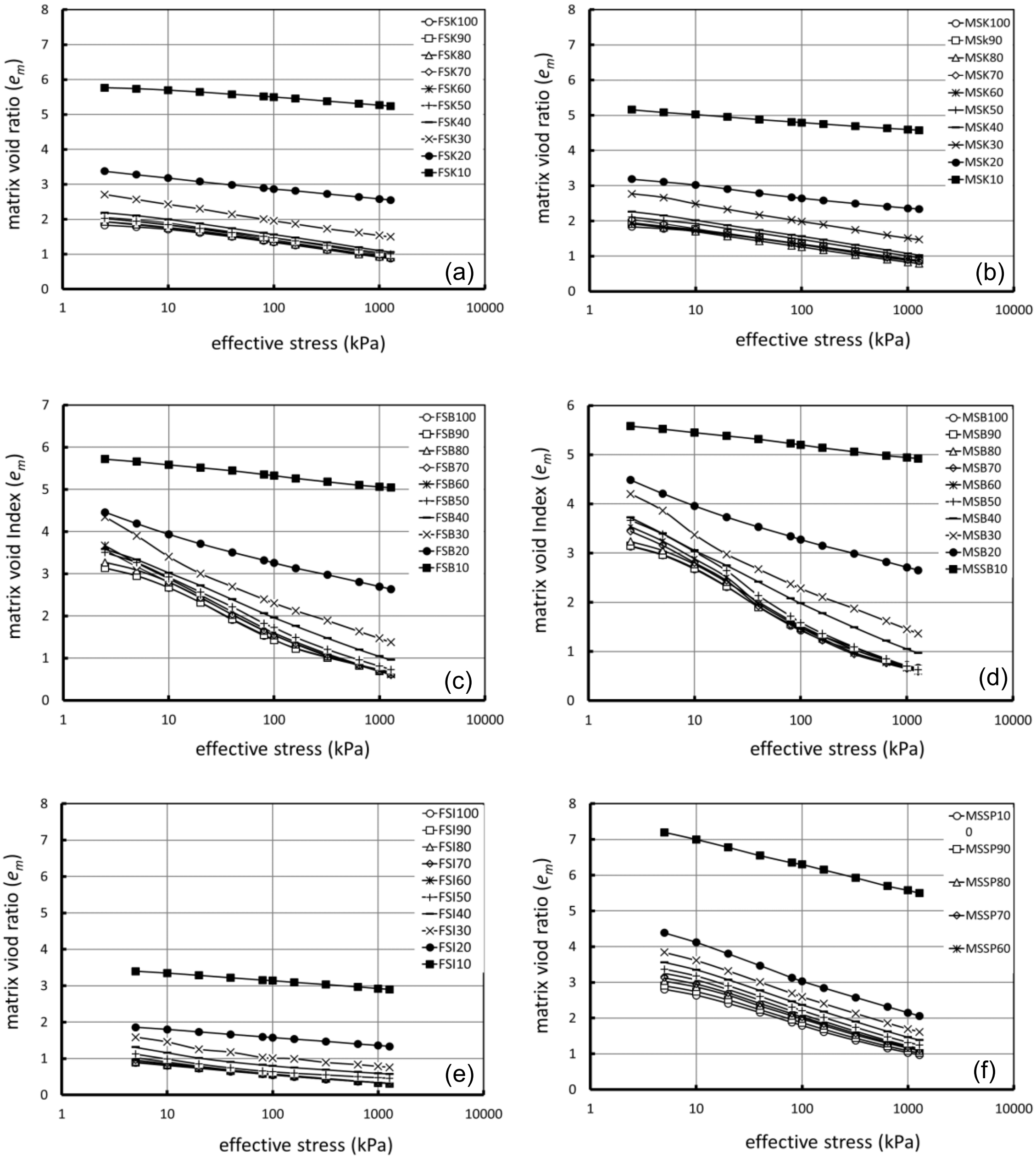


Figure 4.7: The variation of matrix void ratio (e_m) with log effective stress of: (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; (f) medium sand-sepiolite mixtures.

The consolidation curves are approximately linear between 100kPa and 1000kPa for normally consolidated clays (Burland, 1990). This was the stress range used to determine the compression index, C_{c-g}, in the present study for all composite soils (Figure 4.8). This figure illustrates that the compression index decreases as the sand content increases reaching a constant at about 90% sand content. Figure 4.8 also shows that the order of compressibility is sepiolite, bentonite, kaolinite, illite and sand confirming that the compression index, C_{c-g}, is a function of clay type and content.

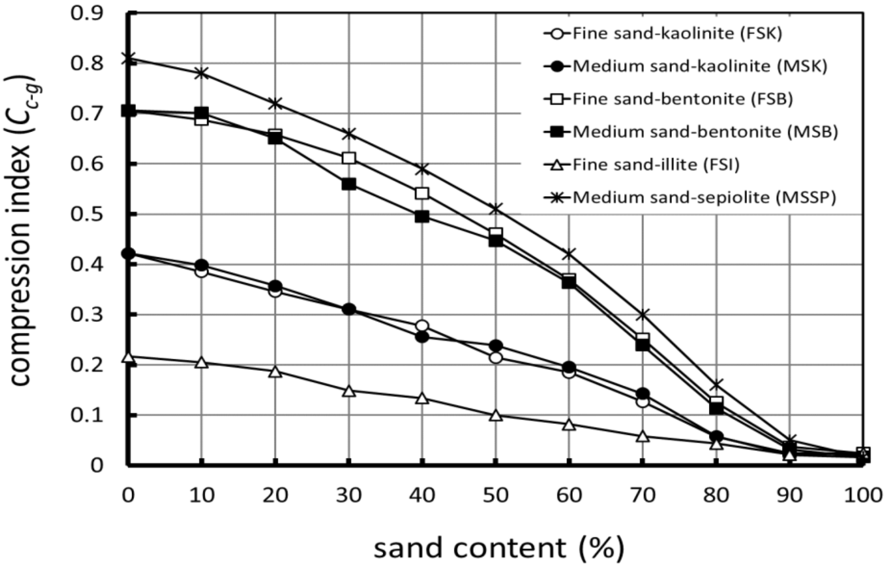


Figure 4.8: Compression index variations with sand content of composite soils

Figure 4.9, compares the present observations on C_{c-g} with published correlations proposed by Skempton (1944), Terzaghi and Peck (1967), Mayhe (1980), and Sridharan and Nagaraj (2000). It can be seen from this figure that, for a liquid limit less than 40%, there is reasonable agreement with all the empirical correlations. However, there is a scatter for the data among the models when the liquid limit exceeds 40%. At a critical sand/clay content, composite soils can be transitional soils; therefore it is necessary, in additional to the liquid limit parameter, to consider the stress state, which, in this case, has been taken as the void ratio at 100kPa. The global compression index data have been replotted, in Figure 4.10, with the void ratio at the liquid limit (e_L) and the global void ratio at 100 kPa confining stress (e_{g100}) to obtain a more representative relationship for C_{c-g} given by:

$$C_{c-g} = 0.053\, e_{g100} + 0.3156\, e_L - 0.099 \tag{4.1}$$

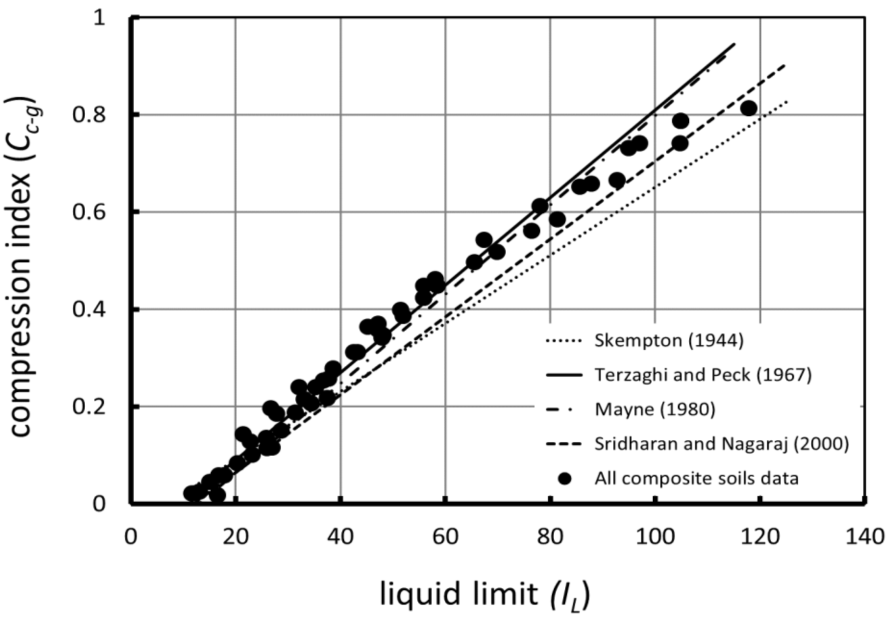


Figure 4.9: A comparison of compression index, $C_{c\text{-}g}$, with published models.

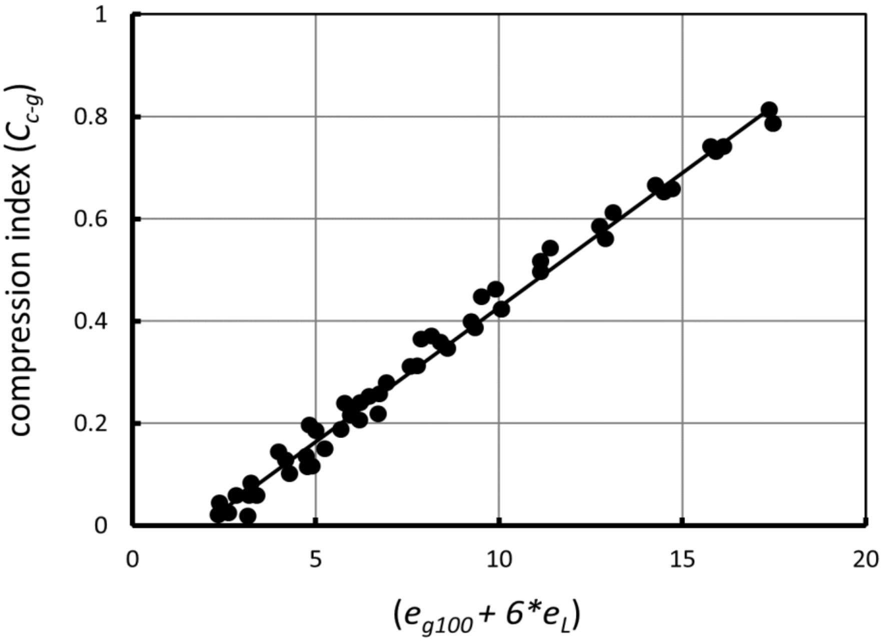


Figure 4.10: Compression index as as a function of void ratios at liquid limit and at100 kPa confining stress.

4.3.1.3 Indirect hydraulic conductivity results

Knowing the values of the coefficient of volume compressibility (m_v) and the coefficient of consolidation (c_v) from consolidation tests, the coefficient of hydraulic conductivity (k_h) was calculated using equ. 3.1. The variation of hydraulic conductivity, k_h, with effective stress, shown in Figure 4.11, suggests that for composite soils, k_h is stress dependent and decreases with clay content. Figure 4.11 also confirms that a composite soil can exist in one of three states:- matrix dominated with clay content in excess of 30% to 40%; clast dominated with clay content less than 20%; and a transition zone with clay content between 20% and 30% or 40% depending on the confining stress and clay type when considering hydraulic conductivity. This is also consistent with those composite soils that exhibit plastic behaviour and those soils which are non-plastic.

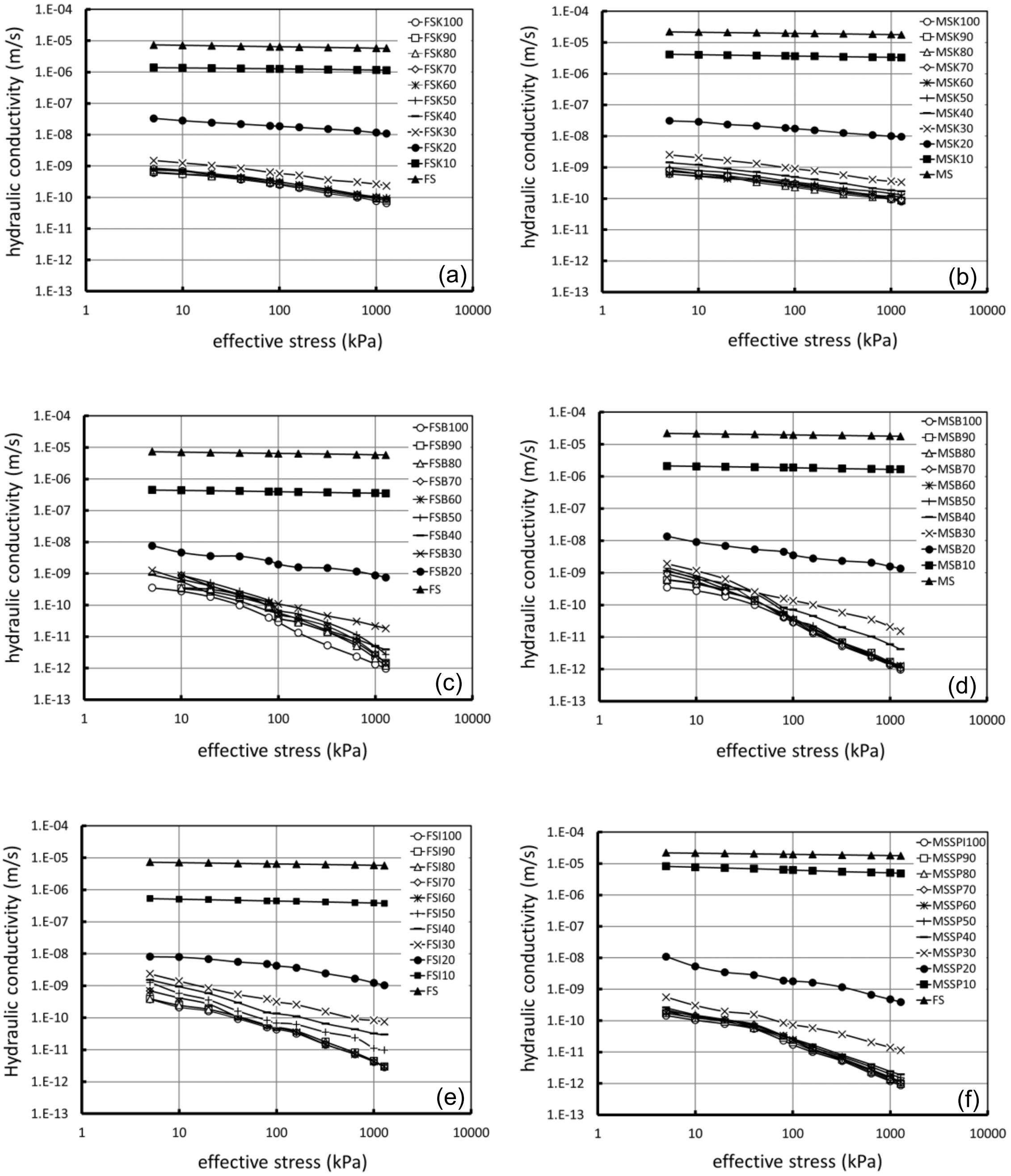


Figure 4.11: The variation of hydraulic conductivity (k_h) with effective stress for (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; (f) medium sand-sepiolite mixtures

The variation of hydraulic conductivity data with global void ratio (e_g) is shown on semi-logarithm plots in Figure 4.12 for all composite soils. As expected, the hydraulic conductivity increases as the global void ratio increases and decreases with increasing clay content. Figure 4.12 shows only the general trend of hydraulic conductivity but does not illustrate clearly any correlation between the soil's composition of clay-sand mixtures (i.e. type and content of clay and sand in the mixture).

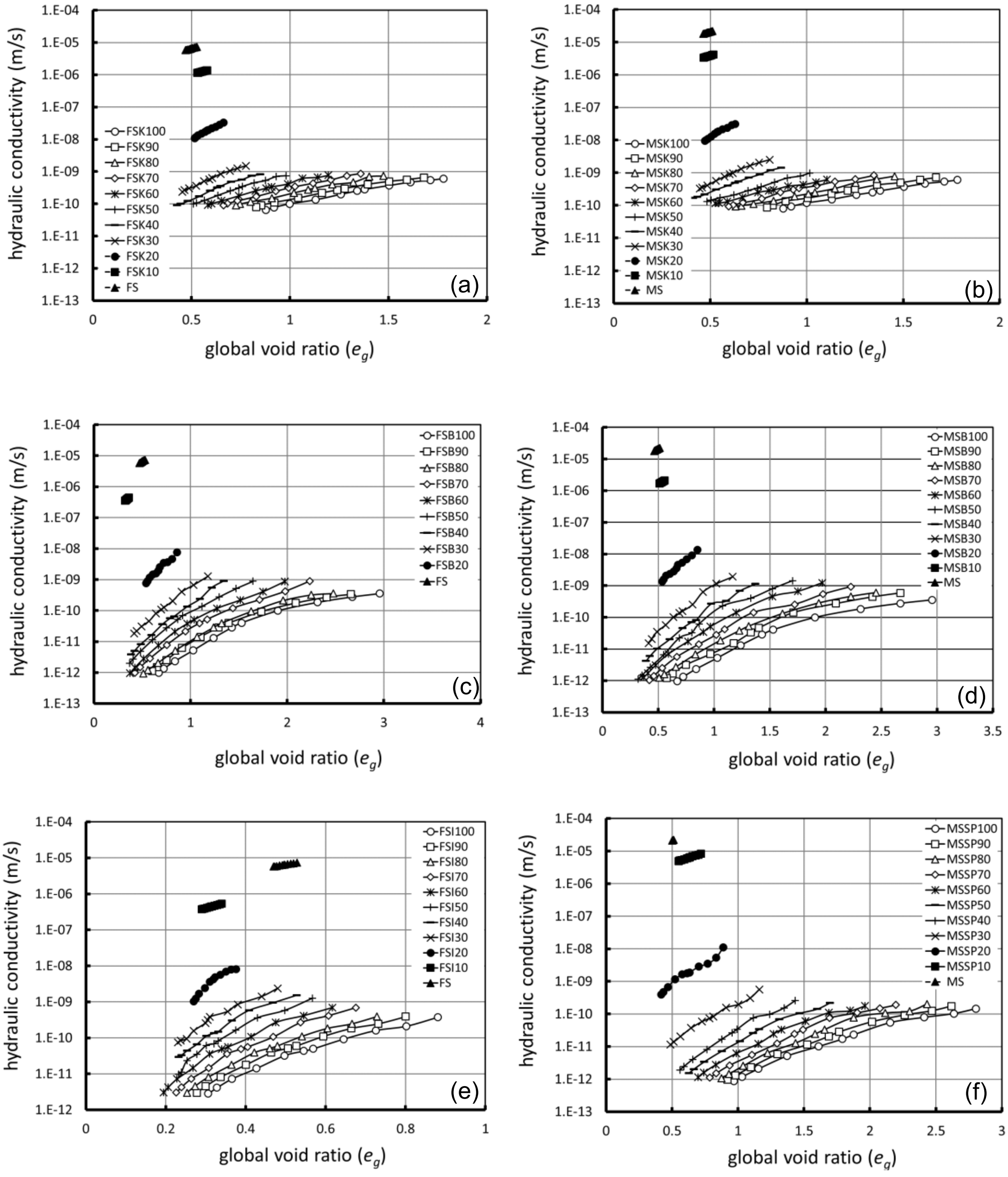


Figure 4.12: The variation of hydraulic conductivity (k_h) with global void ratio for (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; (f) medium sand-sepiolite mixtures

The hydraulic conductivity data was replotted in Figure 4.13 using the matrix void ratio (e_m) in a double-logarithm plot. It can been seen that, for a fine clay content in excess of 30%, the variation in the hydraulic conductivity with effective stress, for a specific type of clay mineral, falls within a narrow band; that is the matrix clay that dominates the permeability of the composite soil.

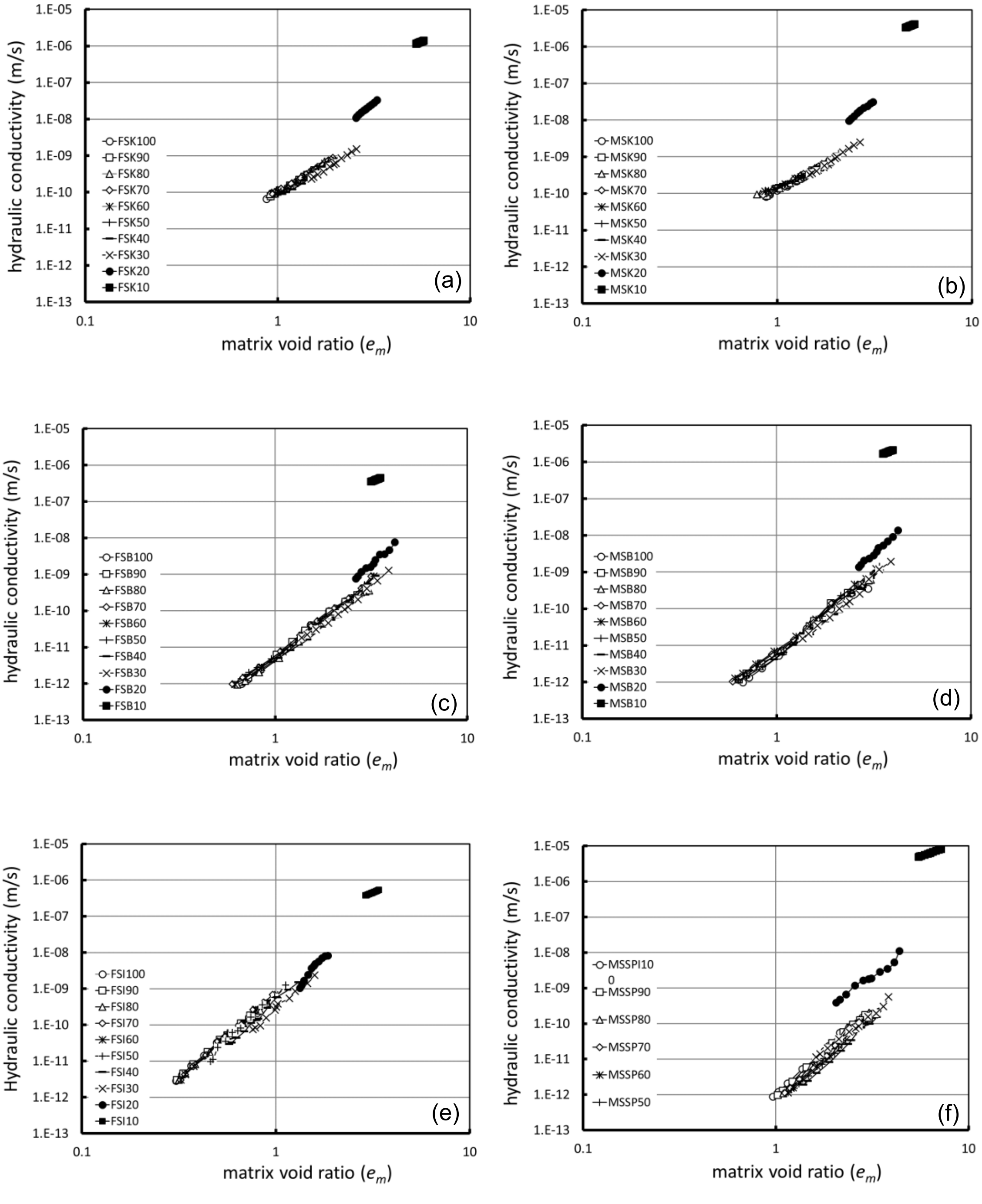


Figure 4.13: The variation of hydraulic conductivity (k_h) with matrix voi ratio for (a) fine sand-kaolinite; (b) medium sand-kaolinite; (c) fine sand-bentonite; (d) medium sand-bentonite; (e) fine sand-illite; (f) medium sand-sepiolite mixtures

The behaviour in Figure 4.13 is consistent with the concept described in Figures 2.2-1A and 2.2-1B, in which the flow is governed by the clay matrix with the coarse particles having little effect provided the sand content is less than 30%. The transitional clay content is shown more clearly in Figure 4.14. In that k_h at a matrix void ratio of one is very nearly constant for all composite soils provided the clay content exceeds 30%.

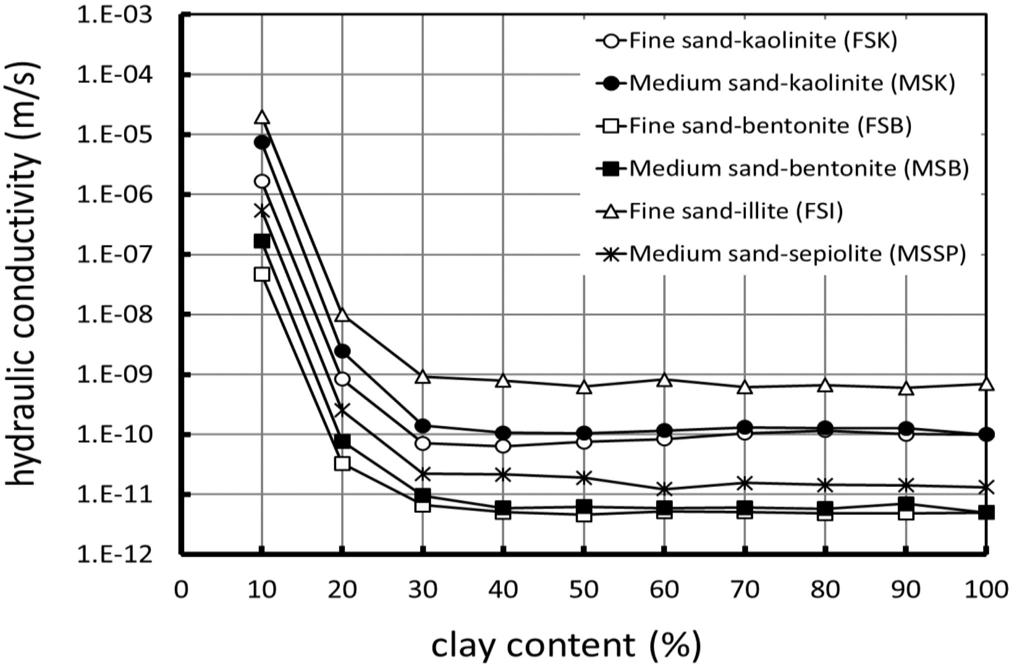


Figure 4.14: Hydraulic conductivity at matrix void ratio of one of all composite soils

Hydraulic conductivity, k_h, of fine grained soils depends on the liquid limit and global void ratio, as shown in Figure 4.15 a. In the case of matrix-dominated composite soils, k_h must depend on the percentage of clay particles and their type, which, collectively, can be expressed as the activity of the clay (A), and the matrix void ratio (e_m). This, as in Figure 4.15b, gives a better fit to the data as the results all fall within a band defined by:

$$k_h = 10^{-10}\left[\frac{1}{A^2}\frac{e_m^3}{1+e_m}\right]^{1.53} \tag{4.2}$$

Figure 4.13 shows that there is no correlation between hydraulic conductivity and matrix void ratio for non-plastic soils. Thevanayagam (1998) and others have suggested that the shear behaviour of clast dominated composite soils is a function of the intergranular void ratio. This also applies to hydraulic conductivity even though the intergranular void ratio includes the fine grained volume. The hydraulic conductivity of coarse grained soils is a function of d_{10} (Hazen, 1892) and the global void ratio (Equ 1) as shown in Figure 4.16a. A better fit to the data is given (Figure 4.16b) if the data for non-plastic soils are expressed in terms of d_{10} and e_i:

$$k_h = 2x10^{-4}\left[d_{10}^2\left(\frac{e_i^3}{1+e_i}\right)\right]^{0.885} \qquad (4.3)$$

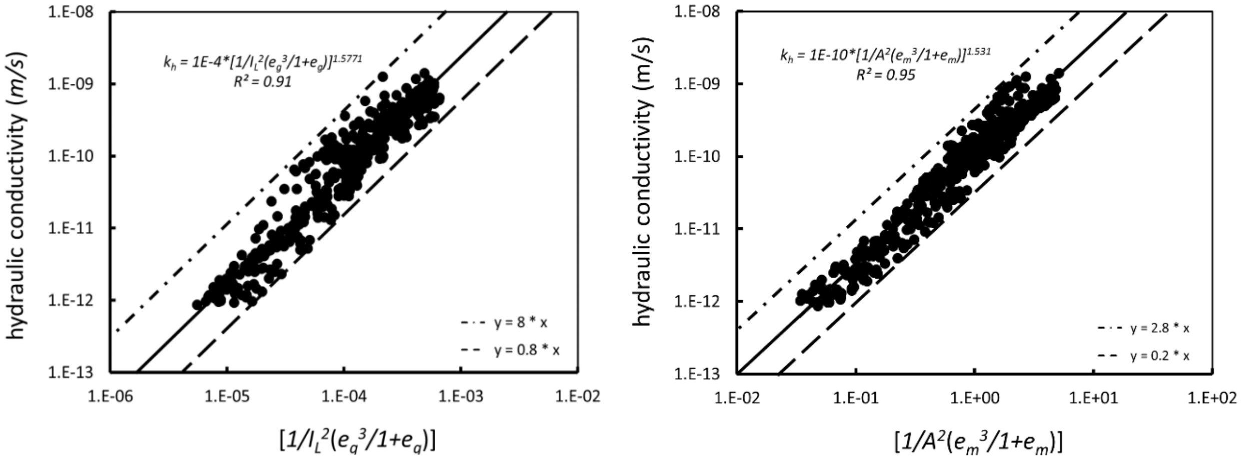


Figure 4.15: The variation of hydraulic conductivity of matrix (fine) dominated composite soils with (a) the global void ratio and liquid limit and (b) the matrix void ratio and activity

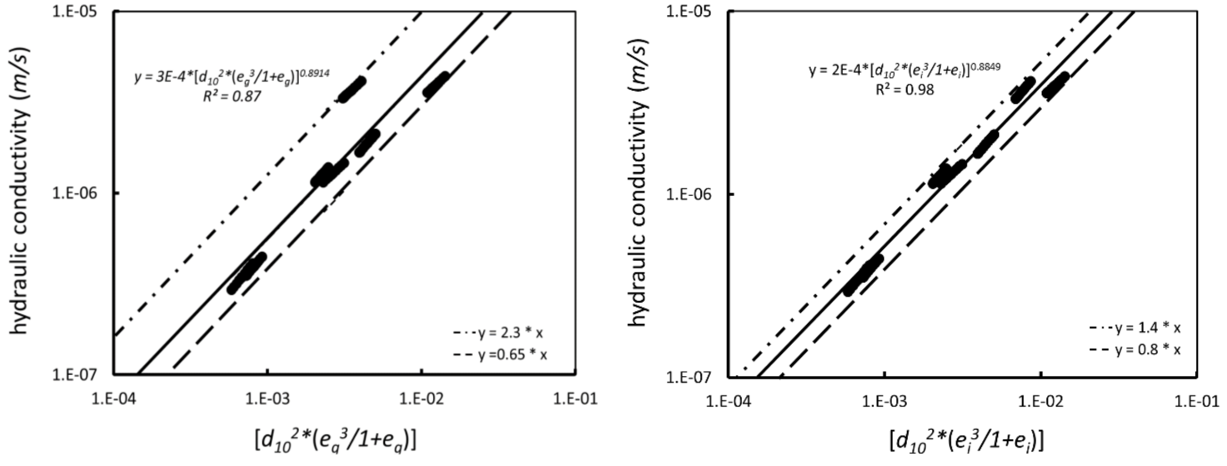


Figure 4.16: The variation of hydraulic conductivity of clast (coarse) dominated composite soils with (a) the global void ratio and (b) the intergranular void ratio.

4.3.2 Direct hydraulic conductivity results

The new conductivity cells were used with two different arrangements in the determination of the coefficient of hydraulic conductivity directly using the principle of Darcy’s law with procedures described in chapter three, section 3.4.4.3.

As mentioned earlier in this chapter, the direct values of the hydraulic conductivity were determined for only one type of composite soil, fine sand-kaolinite mixture, group (1) in Table 4.1 with only (20, 40, 60, 80, 100 % clay content). The results obtained are presented below in Table 4.3.

Table 4.3: The results of hydraulic conductivity of fine sand-kaolinite mixtures using the conductivity cell.

Composite fine sand-kaolinite mixtures	Clay content (C_m %)	Porosity (n)	Global void ratio (e_g)	Matrix void ratio (e_m)	Hydraulic conductivity (k_h) m/s
FSK100	100	0.563	1.300	1.300	3.693E-10
		0.506	1.026	1.026	2.693E-10
		0.492	0.960	0.969	1.803E-10
		0.425	0.741	0.741	1.512E-10
FSK80	80	0.535	1.152	1.440	9.973E-10
		0.449	0.816	1.020	3.566E-10
		0.383	0.621	0.776	3.206E-10
FSK60	60	0.563	1.290	2.151	6.152E-09
		0.467	0.877	1.462	9.383E-10
		0.380	0.614	1.024	1.761E-10
FSK40	40	0.450	0.821	2.052	2.203E-08
		0.387	0.633	1.582	2.203E-09
		0.291	0.411	1.029	8.017E-10
FSK20	20	0.407	0.688	3.444	9.717E-07
		0.325	0.4810	2.407	3.017E-07
		0.306	0.4419	2.209	2.037E-07

Figure 4.17a shows the variations of hydraulic conductivity (k_h) with the global void ratio (e_g) on semi-logarithmic plots for fine sand-kaolinite composite soils. It can be noted, as expected, an increase of the global void ratio and a decrease in clay content leads to an increase in the value of the hydraulic conductivity. A stated in section 4.3.1.3, the global void ratio shows only the general trend of the hydraulic conductivity relationship and does not illustrate the effect of clay/sand content and mineralogy on the hydraulic conductivity. Thus, the data in Figure 4.17a are replotted in Figure 4.17b in terms of matrix void ratio to show the effect of clay content. From Figure 4.17b, it can be seen that the hydraulic conductivity reduces with kaolinite content down to about 40% where

all the results lie within a narrow band ,and for the mixture with 20% kaolinite content, the relationship changes since the sand has a greater influence on the hydraulic conductivity. This means that in fine sand-kaolinite mixtures with kaolinite content in excess of 40%, the kaolinite dominates the hydraulic conductivity. For mixtures with low kaolinite content (20% in Figure 4.17b), the hydraulic conductivity is controlled by the properties of the fine sand found in the mixture.

Figure 4.17b also confirms that the concept of the matrix void ratio can be useful and can be extended for interpreting the hydraulic conductivity results that are measured directly.

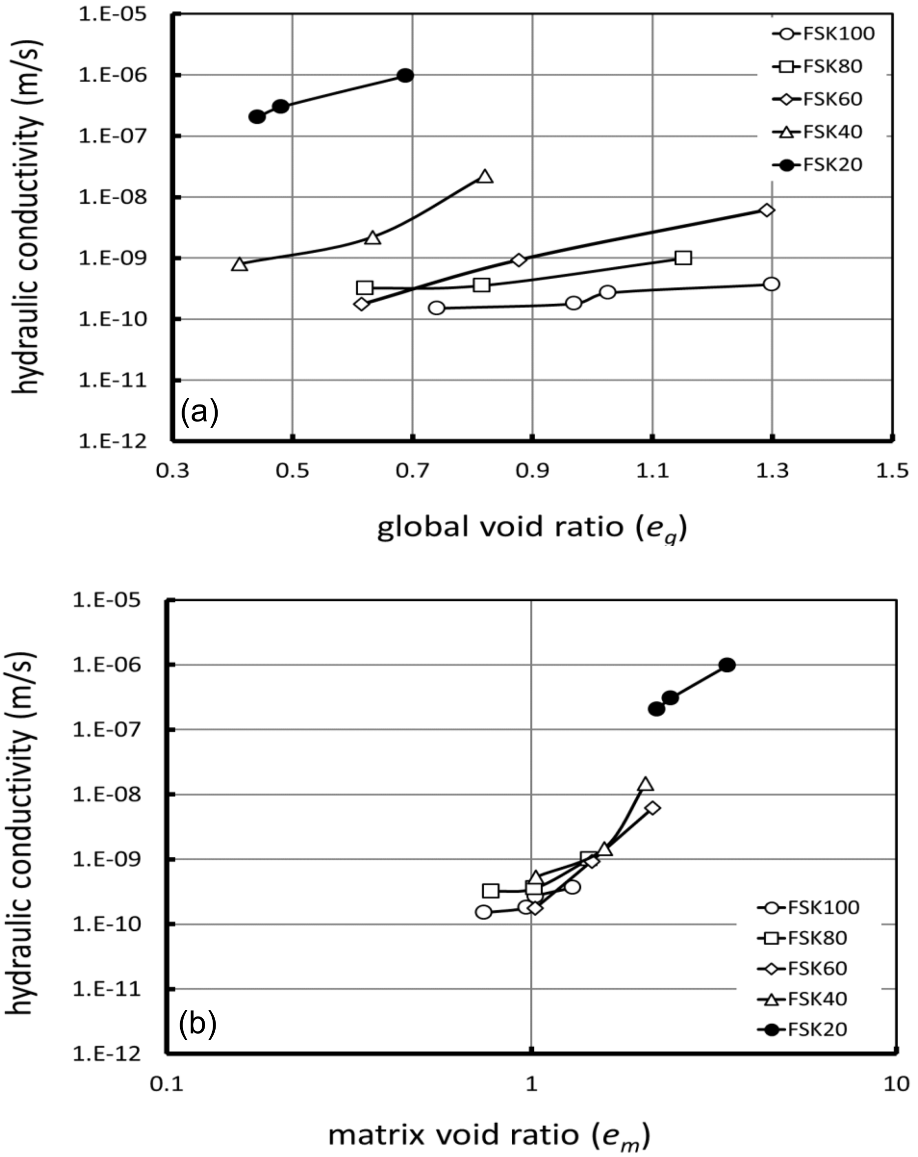
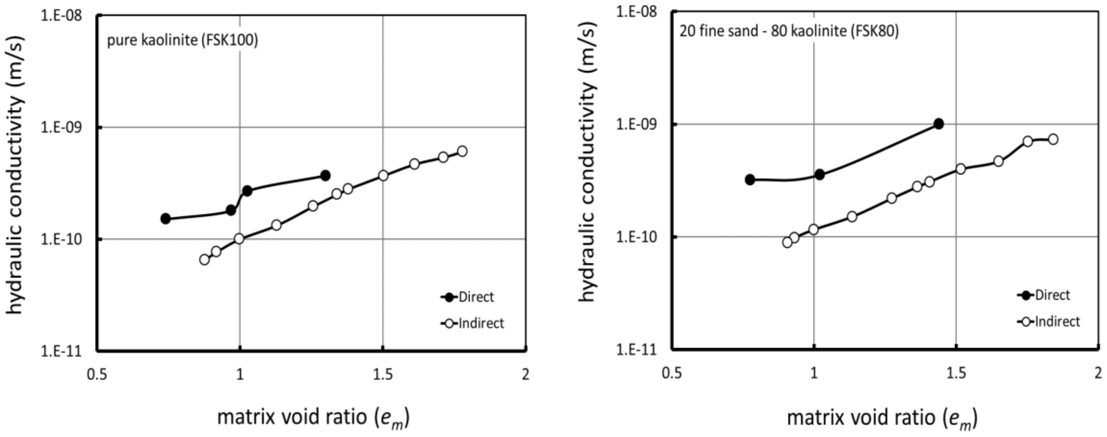


Figure 4.17: The variation of hydraulic conductivity with (a) global void ratio, e_g, (b) matrix void ratio, e_m, of fine sand-kaolinite mixtures

4.4 A comparison between direct and indirect hydraulic conductivity results

Chapuis (2012) and Dafalla et al. (2015) suggested that the indirect assessment based on consolidation test under predicts the hydraulic conductivity in clays by two to three orders of magnitude compared to the measured direct values. Tavenas et al. (1983) reported a similar conclusion for natural soft clays suggesting that the indirect assessment should not be used for estimating the hydraulic conductivity of natural clays. Others (e.g. Terzaghi, 1923; Casagrande and Fadum, 1944), however, found that both calculated and measured values of hydraulic conductivity are essentially similar for a certain type of soils.

To assess to what extent the values of hydraulic conductivity calculated indirectly ($k_{h\text{-}indirect}$) from the consolidation tests vary from those measured directly ($k_{h\text{-}direct}$) from the new conductivity cell, a comparative evaluation was conducted on fine sand-kaolin composite soils using the matrix void ratio (e_m). Figure 4.18 shows the e_m - log k_h relationship for direct and indirect results. In all mixtures, ($k_{h\text{-}indirect}$) is lower than ($k_{h\text{-}direct}$) values by one to two orders of magnitude, and the discrepancy increases as the sand content increases. At a given matrix void ratio, the ratio of ($k_{h\text{-}indirect}$ / $k_{h\text{-}direct}$) ranges from (0.55) for pure kaolinite to (0.034) for fine sand-kaolinite mixture with kaolinite content of 20%. This is possibly due to the assumptions used for the classical Terzaghi's consolidation theory that makes no amendments for the structural viscosity of the soil.



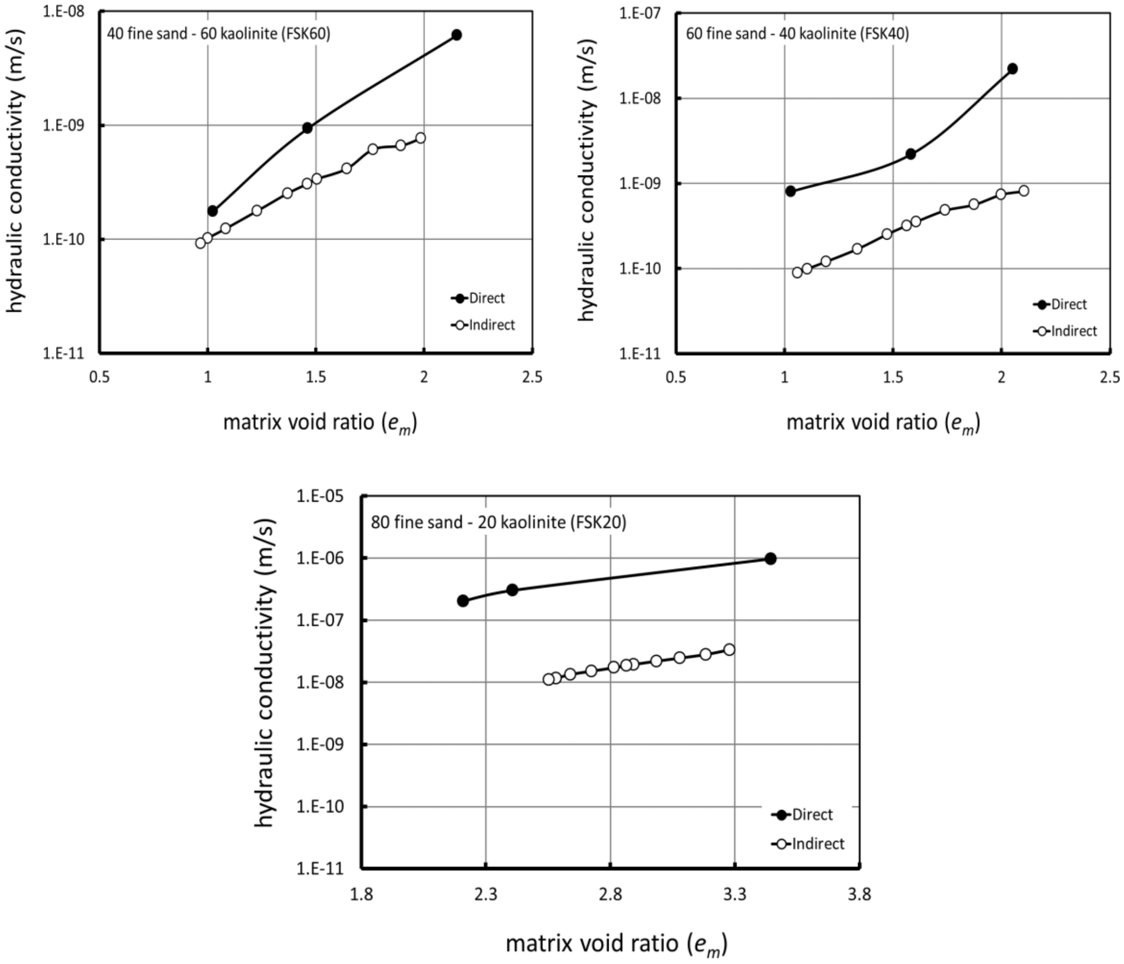


Figure 4.18: A comparison between measured direct conductivity and indirect conductivity from consolidation in fine sand-kaolinite mixtures

4.5 Summary

The results for the hydraulic conductivity of a number of composite soil mixtures obtained from the one-dimensional consolidation tests and those measured directly using the new conductivity cell were presented and analysed. The behaviour of composite soils when the clay dominates the consolidation and hydraulic conductivity and when the sand dictate the behaviour was discussed. The transition zone between clay-dominated and sand-dominated composite soils in the consolidation and hydraulic conductivity, and the possible parameters influencing it was determined with the aid of matrix and intergranular void ratios, density parameters.

New empirical models for the coefficients of consolidation and hydraulic conductivity for composite soils were developed taking into account the effect of soil's composition and physical properties. In these relationships, it can be seen that there is a relationship between the compression index, the void ratio at the liquid limit, and the void ratio at a confining stress of 100kPa which confirms that this index is a function of the clay mineralogy and the density. Moreover, there is a relationship between hydraulic conductivity of composite soils and void ratio. For matrix dominated soils, the relationship is a function of clay type (expressed by activity) and matrix void ratio; for clast dominated soils, it is a function of particle size and intergranular void ratio.

A comparative evaluation between the values of the hydraulic conductivity that were measured directly from the conductivity cell and those that were calculated indirectly from the consolidation was carried out. It was found that in all composite fine sand-kaolinite mixtures, the calculated indirect hydraulic conductivity values are lower by one to two order of magnitude than the measured direct values, and the discrepancy increases as the sand content increases.

Chapter 5

Thermal Conductivity Results of Composite Soils

5.1 Introduction

Test results for thermal conductivity of composite soils made of varying percentages of clays and sands were interpreted and are presented in graphical and tabular styles. The first objective of these tests was to assess the effect that the composition of the soil (water and solids), and its physical properties (water content and dry density) have upon the thermal conductivity of composite soils. The second objective was to evaluate the measured values with those predicted from common thermal models. A more representative heat conduction model is developed based on the thermal and volume properties of soil's constituents.

5.2 Composite soils used for thermal conductivity tests

Thermal conductivity measurements were carried out on soils composed of clay and sand mixtures in proportions by weight of 0, 20, 40, 60, 80, and 100%. Five kinds of clays including kaolinite, bentonite, illite, sepiolite and attapulgite and three types of sands, fine sand, medium sand and mixed sand were used in the thermal experiments. While the kaolinite, bentonite, illite, sepiolite, fine sand and medium sand have the same properties to those used in the hydraulic conductivity measurements, attapulgite clay and sand consisting of fractions 5%A, 40%B, 40%C, and 15%D were also tested. The physical and mineralogical properties of clays and sands used is presented in Table 3.1.

Six groups of composite soils mixtures were prepared and used for thermal conductivity tests (Table 5.1). Note that the index properties (i.e. Atterberg limits and specific gravity) of all mixtures were determined following the procedures in BS EN ISO 17892-12:2018 and BS 1377-2:1990 but based on the whole sample rather than particles smaller than 425μm.

Table 5.1: Composite soils used for thermal conductivity measurements

Groups	Samples	Symbol	Clay content (C_m %)	Sand content (S_m %)	Specific gravity (G_T)	Liquid limit (I_L %)	Plastic limit (I_P %)	Plasticity index (PI %)	Mean particle size (mm)
1	Kaolinite	SK100	100	0	2.60	56.0	33.0	23.0	
	Mixed sand - Kaolinite	SK80	80	20	2.61	48.1	29.0	19.2	
	Mixed sand - Kaolinite	SK60	60	40	2.62	38.4	23.7	15.0	
	Mixed sand - Kaolinite	SK40	40	60	2.63	27.8	16.4	11.5	
	Mixed sand - Kaolinite	SK20	20	80	2.64	17.2	-	-	
	Mixed sand	S	0	100	2.65	-	-	-	0.69
2	Fine sand - kaolinite	FSK80	80	20	2.60	48.2	28.8	19.4	
	Fine sand - kaolinite	FSK60	60	40	2.61	38.7	23.0	15.7	
	Fine sand - kaolinite	FSK40	40	60	2.62	27.9	15.4	12.5	
	Fine sand - kaolinite	FSK20	20	80	2.63	17.9	-	-	
	Fine sand	FS	0	100	2.63	-	-	-	0.225
3	Calcium bentonite	SB100	100	0	2.55	105.0	48.0	57.0	
	Mixed sand + Bentonite	SB80	80	20	2.57	87.2	41.6	46.3	
	Mixed sand + Bentonite	SB60	60	40	2.59	66.9	30.1	37.4	
	Mixed sand + Bentonite	SB40	40	60	2.61	46.9	22.7	24.6	
	Mixed sand + Bentonite	SB20	20	80	2.63	26.7	-	-	
4	illite	FSI100	100	0	2.67	37.6	20.0	17.6	
	Fine sand - illite	FSI80	80	20	2.66	31.5	16.2	15.3	
	Fine sand - illite	FSI60	60	40	2.65	26.0	13.1	12.9	
	Fine sand - illite	FSI40	40	60	2.64	20.5	-	-	
	Fine sand - illite	FSI20	20	80	2.63	15.2	-	-	
5	Sepiolite	MSSP100	100	0	2.30	118.0	86.5	31.5	
	Medium sand - Sepiolite	MSSP80	80	20	2.38	92.9	69.0	23.9	
	Medium sand - Sepiolite	MSSP60	60	40	2.46	70.0	51.2	18.8	
	Medium sand - Sepiolite	MSSP40	40	60	2.54	48.0	35.5	12.5	
	Medium sand - Sepiolite	MSSP20	20	80	2.61	25.1	-	-	
	Medium sand	MS	0	100	2.64	-	-	-	0.45
6	Attapulgite	MSAG100	100	0	2.08	225.0	126	99.0	
	Medium sand - Attapulgite	MSAG80	80	20	2.20	187.0	105	82.0	
	Medium sand - Attapulgite	MSAG60	60	40	2.33	136.0	80.2	55.8	
	Medium sand - Attapulgite	MSAG40	40	60	2.50	92.0	50.1	41.9	
	Medium sand - Attapulgite	MSAG20	20	80	2.58	50.0	-	-	

*S= mixed sand; FS= fine sand; MS= medium sand; K= kaolinite; B= bentonite; I= illite; SP= sepiolite; AG= attapulgite

5.3 Thermal conductivity results of composite soils

Thirty two thermal experiments were performed, and the data obtained were correlated with physical and mineralogical properties of the composite soils. The composite soil samples were prepared and consolidated inside the conductivity cells and then tested based on the test procedures given in Chapter three.

The typical variation of temperature with time for saturated clays (kaolinite, bentonite, illite, sepiolite, and attapulgite), and sands (fine sand, medium sand and mixed sand), the soil particles used to form composite soil mixtures, is shown in Figure 5.1 and Figure 5.2, respectively. The temperatures in these figures were recorded at the base of the cell (base of the sample) for the heat source, and at three different points inside the sample at distances 10, 50, 90 mm from the heating source. When the power was switched on, the temperatures began to increase gradually until they reached a maximum after 19, 23, 19, 26, 24 hrs in case of kaolinite, bentonite, illite, sepiolite an attapulgite clays and after 20, 19, 17 hrs for fine, medium and mixed sands, respectively. The maximum temperature varies with respect to the distance from the heat source.

Figure 5.1 and Figure 5.2 show that the increase in temperature in sands generally exceeded that for clays and the time needed to reach the maximum temperature was shorter for sands than for clays. This is because sands particles have a higher thermal conductivity than clays and thus heat will transfer through them more rapidly. Figure 5.1 and Figure 5.2 also illustrate that the temperature difference between any two points along the axis of the sands samples is less than that in clays, which means that the thermal conductivity of sands is greater.

It should be noted that the physical properties of the sands and clays in Figure 5.1 and Figure 5.2 varies which could also affect the temperature variations. For example, in Figure 5.1, kaolinite needs shorter time, 19 hrs, to reach the maximum temperature values in compared to bentonite, 23 hrs or attapulgite, 24 hrs. This could be possibly due to the dry density in kaolinite, p_d = 1.49 Mg/m^3, is higher than that in bentonite, 1.17 Mg/m^3 and in attapulgite, 0.63 Mg/m^3, which is a function of the clay mineralogy. An increase in dry density because of the type of clay implies an increase in solids content and therefore a more conductive soil. Therefore, it is expected that the thermal conductivity is affected by the sand/clay content, clay mineralogy and the physical properties of the soils. This will be assessed later in this chapter in more detail.

Once the steady state condition was established in Figure 5.1 and Figure 5.2, the power was turned off and the temperature was left to reduce to the room temperature, under the free or natural convection from the ends of the sample.

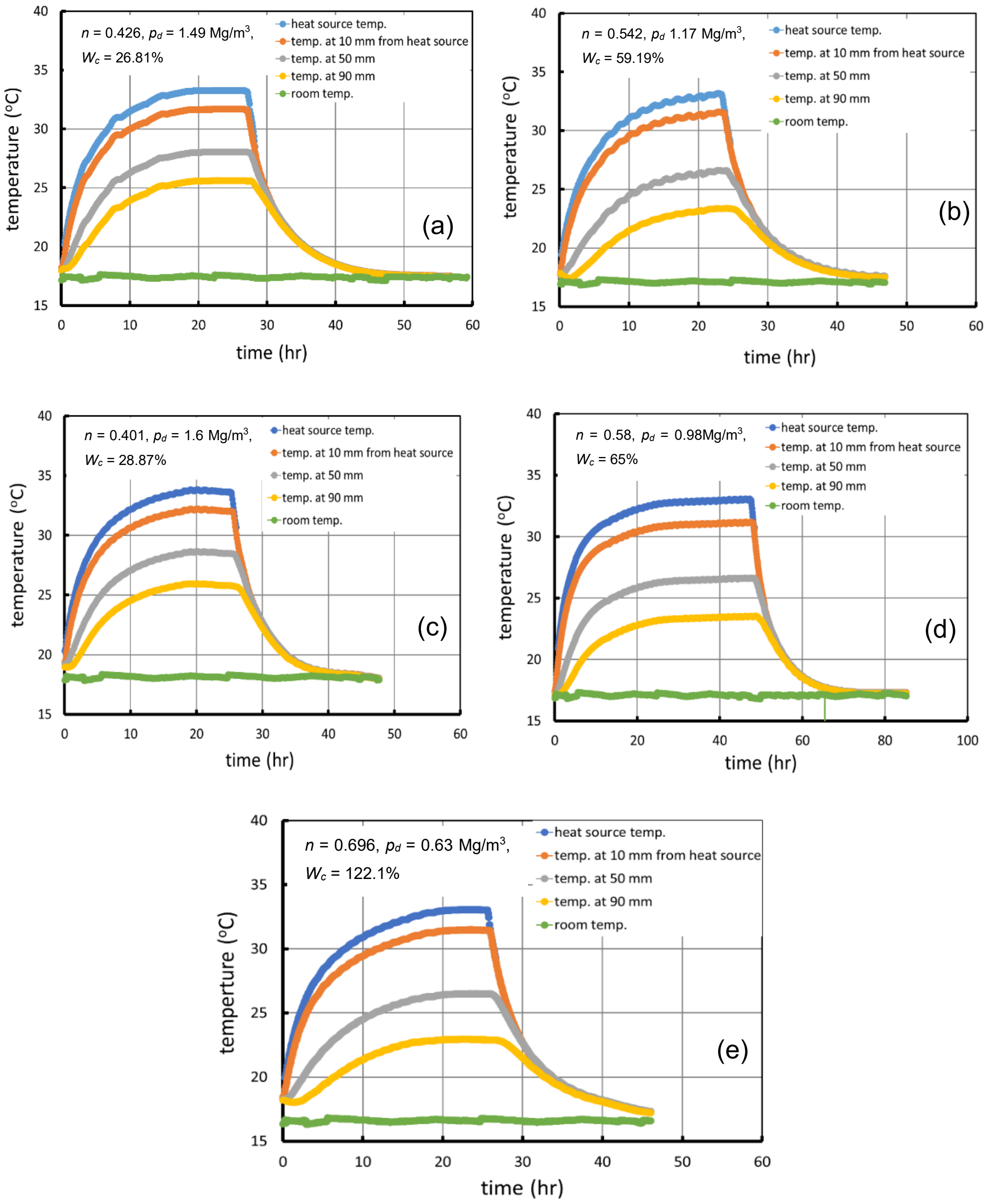


Figure 5.1: Typical profile of temperature vs time of saturated clays; (a) kaolinite, (b) bentonite, (c) illite, (d) sepiolite, (e) attapulgite

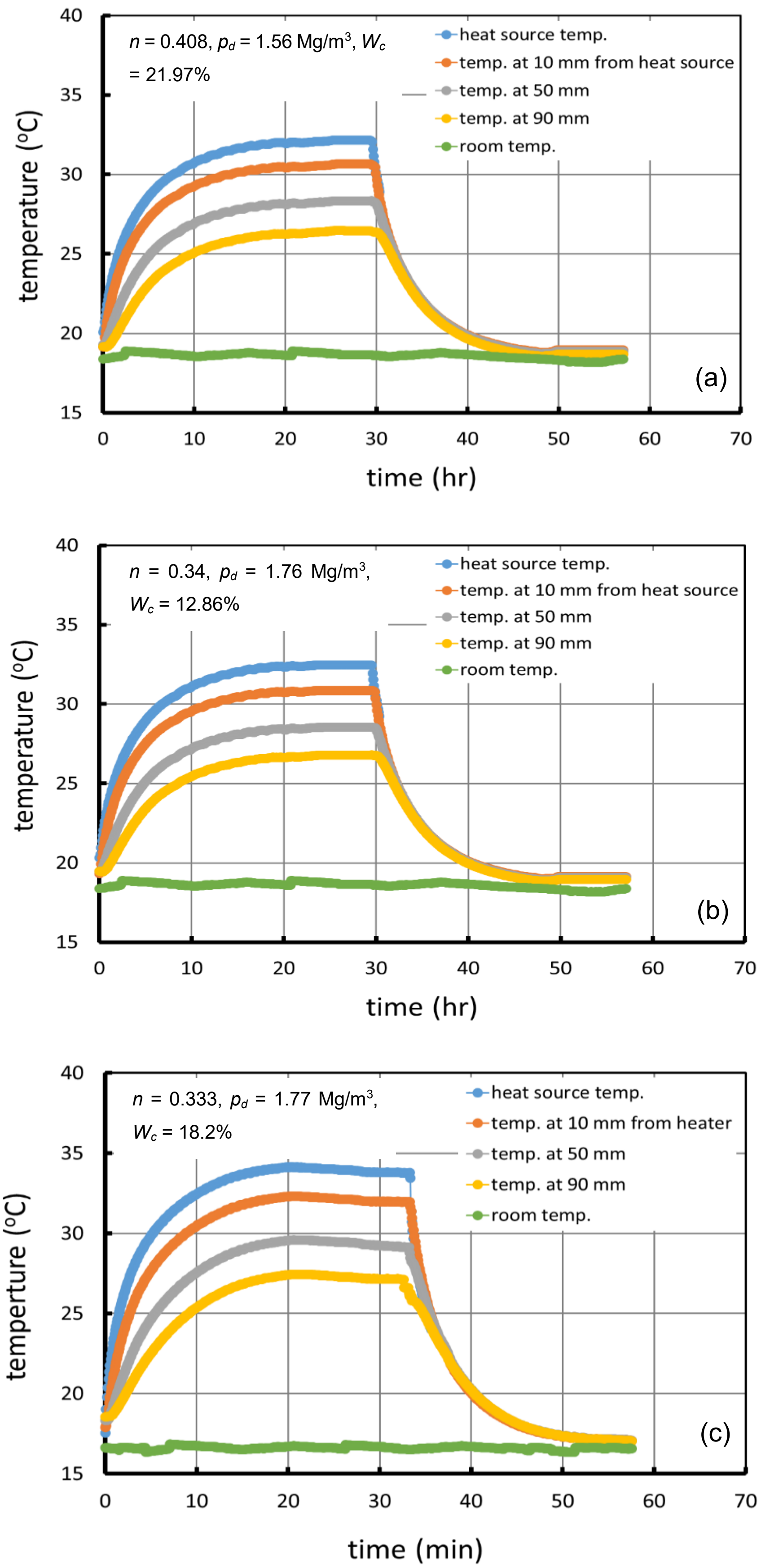


Figure 5.2: Typical profile of temperature vs time of saturated sands; (a) fine sand, (b) medium sand, (c) mixed sand

The coefficient of the thermal conductivity of all composite soil mixtures was determined following the procedures that have been described in chapter three, section 3.4.4.4, and a summary of the results is presented in Tables 5.2, 5.3, 5.4, 5.5, 5.6 and 5.7 for all composite soil mixtures.

Table 5.2: The thermal conductivity results of composite mixed sand-kaolinite mixtures

Composite mixed sand-kaolinite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio n	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Thermal conductivity (W/m .^{o}C)
SK100	100	0	0.536	0.536	-	1.21	45.96	1.538
			0.507	0.507	-	1.28	37.60	1.708
			0.492	0.492	-	1.32	36.12	1.723
			0.426	0.426	-	1.49	26.81	1.808
SK80	80	20	0.539	0.594	0.908	1.20	46.94	1.769
			0.482	0.537	0.896	1.35	36.25	1.920
			0.447	0.503	0.889	1.44	31.83	1.889
			0.378	0.432	0.876	1.62	24.34	2.052
SK60	60	40	0.535	0.657	0.814	1.22	48.32	1.802
			0.467	0.594	0.787	1.40	37.79	2.119
			0.389	0.515	0.756	1.60	28.13	2.284
SK40	40	60	0.460	0.681	0.676	1.42	35.81	2.051
			0.399	0.624	0.639	1.58	28.83	2.381
			0.360	0.584	0.616	1.60	25.15	2.469
			0.331	0.553	0.598	1.76	21.68	2.538
SK20	20	80	0.373	0.748	0.498	1.66	25.80	2.662
			0.330	0.711	0.464	1.70	23.00	2.715
			0.301	0.683	0.441	1.84	18.97	2.809
			0.274	0.653	0.419	1.92	15.00	2.862
S	0	100	0.333	-	0.333	1.77	18.20	2.938
			0.323	-	0.323	1.79	16.28	2.972
			0.302	-	0.302	1.85	12.86	3.008

Table 5.3: The thermal conductivity results of composite mixed sand-bentonite mixtures

Composite mixed sand-bentonite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio *n*	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Thermal conductivity (W/m .^{o}C)
SB100	100	0	0.710	0.710	-	0.74	104.18	1.77
			0.655	0.655	-	0.88	79.68	1.244
			0.630	0.630	-	0.94	73.00	1.292
			0.591	0.591	-	1.04	62.84	1.361
			0.542	0.542	-	1.17	59.19	1.369
SB80	80	20	0.588	0.836	0.918	1.06	65.00	1.455
			0.543	0.809	0.909	1.15	55.00	1.538
			0.487	0.772	0.897	1.30	45.00	1.692
			0.450	0.745	0.890	1.41	39.76	1.785
SB60	60	40	0.543	0.664	0.817	1.18	51.85	1.629
			0.487	0.613	0.795	1.33	40.58	1.846
			0.440	0.567	0.776	1.40	35.00	1.923
			0.410	0.537	0.764	1.53	32.00	1.977
SB40	40	60	0.519	0.730	0.711	1.26	45.27	1.762
			0.459	0.680	0.676	1.41	36.79	1.985
			0.393	0.618	0.636	1.58	29.18	2.300
			0.370	0.595	0.622	1.64	27.01	2.269
SB20	20	80	0.501	0.834	0.601	1.31	40.17	2.009
			0.456	0.807	0.565	1.43	32.00	2.175
			0.399	0.768	0.519	1.50	26.69	2.233
			0.350	0.729	0.480	1.70	23.60	2.277
S	0	100	0.333	-	0.333	1.77	18.20	2.938
			0.323	-	0.323	1.79	16.28	2.972
			0.302	-	0.302	1.85	12.86	3.008

Table 5.4: The thermal conductivity results of composite fine sand-kaolinite mixtures

Composite fine sand-kaolinite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio n	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Thermal conductivity (W/m .ºC)
FSK100	100	0	0.536	0.536	-	1.21	45.96	1.538
			0.507	0.507	-	1.28	37.60	1.708
			0.492	0.492	-	1.32	36.12	1.692
			0.426	0.426	-	1.49	26.81	1.808
FSK80	80	20	0.535	0.590	0.907	1.21	49.22	1.699
			0.500	0.556	0.900	1.26	43.64	1.746
			0.450	0.505	0.890	1.43	36.43	1.822
			0.383	0.437	0.877	1.60	28.26	1.842
FSK60	60	40	0.563	0.683	0.825	1.14	52.83	1.853
			0.467	0.594	0.787	1.39	37.86	1.979
			0.381	0.506	0.752	1.62	28.05	2.049
FSK40	40	60	0.506	0.719	0.703	1.30	41.85	2.009
			0.430	0.653	0.658	1.45	31.95	2.254
			0.388	0.613	0.633	1.60	27.23	2.408
FSK20	20	80	0.408	0.775	0.526	1.56	26.85	2.500
			0.325	0.707	0.460	1.78	19.30	2.878
			0.307	0.688	0.445	1.82	17.91	3.012
			0.290	0.671	0.432	1.84	16.76	3.062
FS	0	100	0.408	-	0.408	1.56	21.97	2.812
			0.390	-	0.390	1.64	18.20	2.980
			0.370	-	0.370	1.68	16.28	3.015

Table 5.5: The thermal conductivity results of composite fine sand-illite mixtures

Composite fine sand-illite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio n	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Thermal conductivity (W/m .^{o}C)
FSI100	100	0	0.512	0.512	-	1.30	43.21	1.623
			0.401	0.401	-	1.60	28.87	1.769
			0.317	0.317	-	1.82	23.00	1.923
FSI80	80	20	0.470	0.526	0.894	1.41	37.43	1.700
			0.380	0.434	0.876	1.65	26.48	2.000
			0.290	0.338	0.858	1.89	17.58	2.308
FSI60	60	40	0.440	0.567	0.776	1.48	33.55	1.930
			0.380	0.505	0.752	1.64	24.48	2.154
			0.270	0.381	0.708	1.93	15.88	2.385
FSI40	40	60	0.380	0.605	0.628	1.64	25.00	2.238
			0.330	0.552	0.598	1.77	20.00	2.385
			0.240	0.441	0.544	2.01	13.00	2.769
FSI20	20	80	0.341	0.721	0.472	1.73	20.80	2.635
			0.297	0.679	0.438	1.85	16.99	2.941
			0.263	0.641	0.410	1.94	14.40	3.077
FS	0	100	0.408	-	0.408	1.56	21.97	2.812
			0.390	-	0.390	1.64	18.20	2.980
			0.370	-	0.370	1.68	16.28	3.015

Table 5.6: The thermal conductivity results of composite medium sand-sepiolite mixtures

Composite medium sand-sepiolite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio n	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Thermal conductivity (W/m .ºC)
MSSP100	100	0	0.695	0.695	-	0.70	106.15	1.297
			0.637	0.637	-	0.83	82.77	1.329
			0.600	0.600	-	0.90	71.49	1.358
			0.580	0.580	-	0.98	65.00	1.401
MSSP80	80	20	0.653	0.701	0.931	0.83	84.26	1.437
			0.598	0.651	0.920	0.96	68.55	1.453
			0.543	0.598	0.909	1.09	56.12	1.481
			0.525	0.580	0.905	1.20	52.77	1.491
MSSP60	60	40	0.630	0.739	0.852	0.90	67.55	1.553
			0.560	0.680	0.824	1.10	55.12	1.581
			0.490	0.616	0.796	1.25	50.77	1.608
			0.470	0.596	0.788	1.40	45.00	1.640
MSSP40	40	60	0.590	0.783	0.754	1.04	60.00	1.701
			0.519	0.729	0.711	1.22	45.96	1.858
			0.470	0.689	0.682	1.36	38.88	1.962
			0.428	0.651	0.657	1.45	34.40	2.052
MSSP20	20	80	0.486	0.826	0.589	1.34	37.50	2.230
			0.412	0.778	0.530	1.53	29.08	2.408
			0.370	0.746	0.496	1.59	24.53	2.504
			0.356	0.734	0.485	1.68	23.03	2.536
MS	0	100	0.364	-	0.364	1.68	18.91	2.779
			0.353	-	0.353	1.72	16.28	2.822
			0.340	-	0.340	1.76	12.86	2.848

Table 5.7: The thermal conductivity results of composite medium sand-attapulgite mixtures

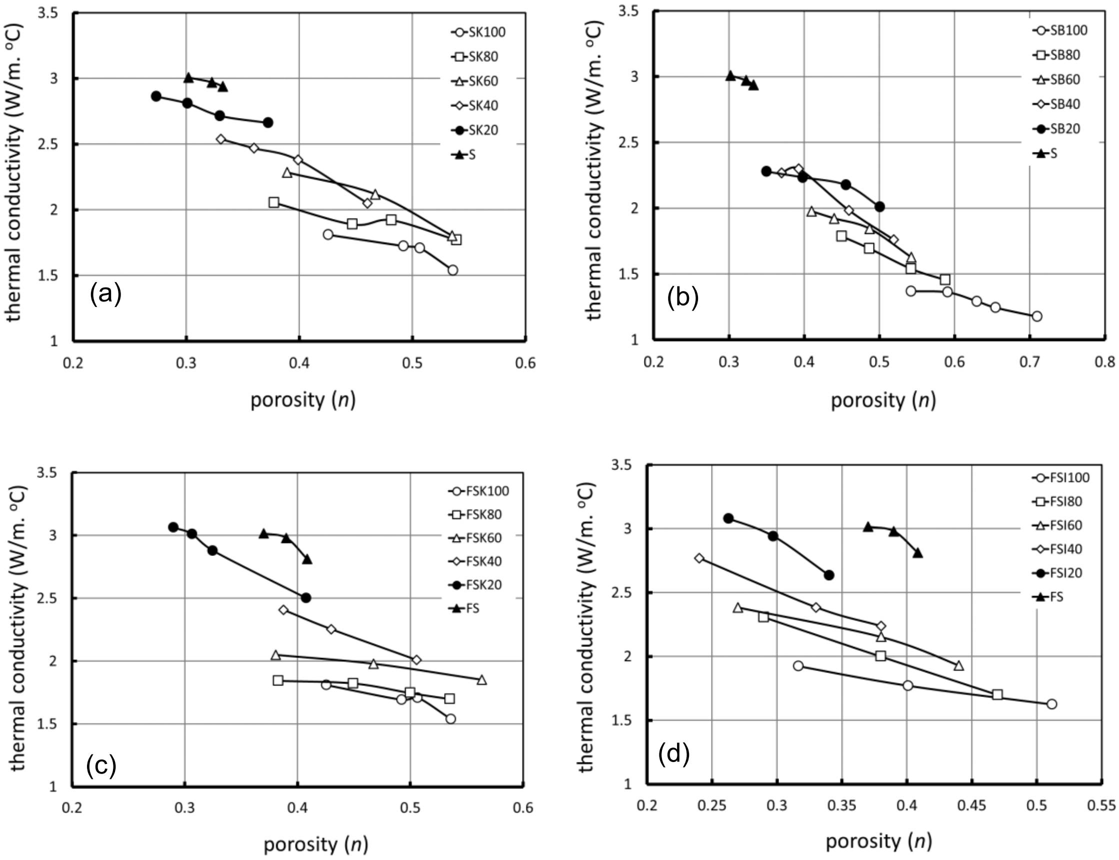
Composite medium sand-attapulgite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio n	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Thermal conductivity (W/m .^{o}C)
MSAG100	100	0	0.807	0.807	-	0.40	210.68	1.226
			0.763	0.763	-	0.49	167.63	1.256
			0.696	0.696	-	0.63	122.07	1.275
			0.640	0.640	-	0.70	102.55	1.282
MSAG80	80	20	0.786	0.821	0.957	0.47	175.51	1.260
			0.712	0.756	0.942	0.63	122.71	1.318
			0.640	0.690	0.928	0.86	88.87	1.377
			0.586	0.639	0.917	0.91	74.71	1.400
MSAG60	60	40	0.761	0.841	0.904	0.56	143.06	1.315
			0.689	0.787	0.876	0.72	102.34	1.354
			0.600	0.714	0.840	1.00	68.01	1.485
			0.489	0.615	0.796	1.19	50.21	1.566
MSAG40	40	60	0.685	0.845	0.811	0.77	95.34	1.377
			0.543	0.748	0.726	1.12	55.56	1.711
			0.500	0.715	0.700	1.22	46.71	1.808
			0.480	0.698	0.688	1.32	37.00	1.915
MSAG20	20	80	0.486	0.826	0.589	1.30	41.00	2.004
			0.412	0.778	0.530	1.45	32.00	2.202
			0.370	0.746	0.496	1.56	28.00	2.401
			0.356	0.734	0.485	1.60	26.00	2.610
MS	0	100	0.364	-	0.364	1.68	18.91	2.779
			0.353	-	0.353	1.72	16.28	2.822
			0.340	-	0.340	1.76	12.86	2.848

5.3.1 Effect of soil composition on thermal conductivity

As mentioned in section 2.6.2.1 and seen in Figure 5.1 and Figure 5.2, the thermal conductivity of soils is influenced by the composition of the soil particles, the density of packing, and the water content. The clay mineralogy, clay/sand content and dry density were varied to show how the coefficient of thermal conductivity varies with the change in the volume fraction of water and solid particles.

5.3.1.1 Volume fraction of water (porosity)

In saturated soils, the volumetric fraction of water is equal to the porosity of the soil. The effect of porosity on the thermal conductivity of different mixtures of composite soils is presented in Figure 5.3. For a specific type of composite soil, an increase in porosity (water fraction) implies a decrease in the thermal conductivity of the soils and, for each soil mix, the relationship is nearly linear. This is normal as the thermal conductivity of the water is much lower than that of soil particles (clay and sand particles).



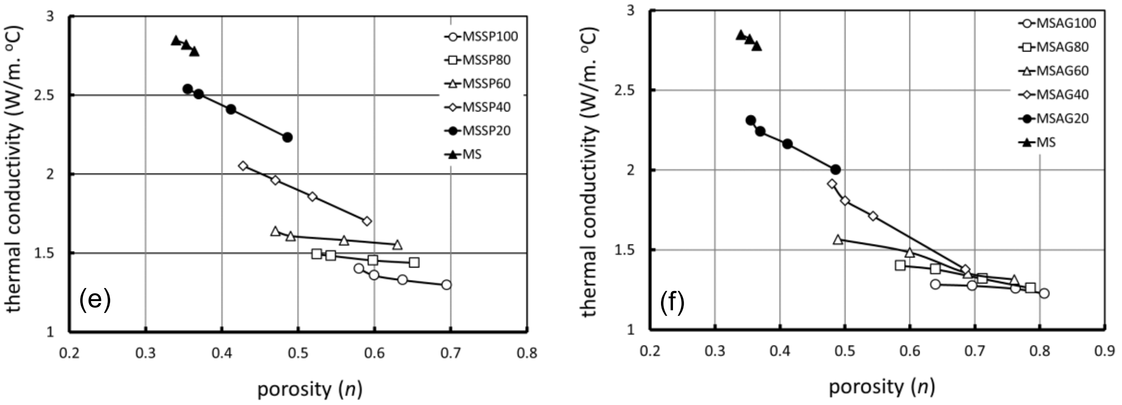


Figure 5.3: Porosity effect on the thermal conductivity of: (a) mixed sand-kaolinite, (b) mixed sand-bentonite, (c) fine sand-kaolinite, (d) fine sand-illite, (e) medium sand-sepiolite, (f) medium sand-attapulgite mixtures

5.3.1.2 Sand content

An increase in sand content is expected to lead to an increase in thermal conductivity of the soil because the thermal conductivity of the sand particles exceeds that of clay minerals. The comparison with sand content is based on a common porosity so that the effect of the water fraction is the same for all samples.

The values of thermal conductivity are plotted against sand content in Figure 5.4. Each data point at a given sand content represents a different porosity as the soil was consolidated between measurements of temperature to determine the effect of water content. The solid line represents the best fit for the values of the thermal conductivity at porosity, n = 0.5, the most common porosity among all mixtures' porosities. The thermal conductivity at n = 0.5 that is shown with solid markers in Figure 5.4, was determined from the best-fit equation of (k_t-n) relationship.

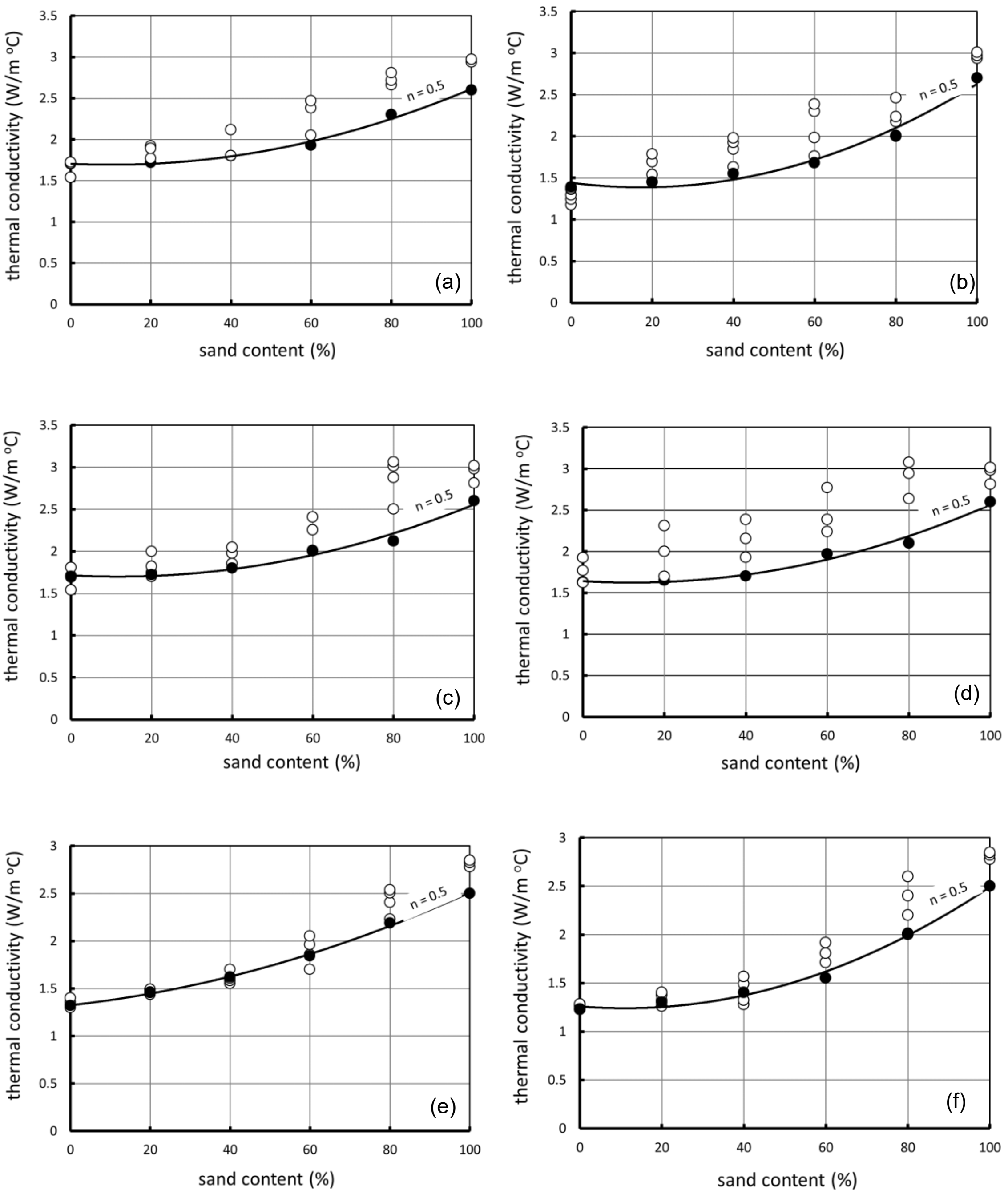


Figure 5.4: Sand content effect on the thermal conductivity of (a) mixed sand-kaolinite, (b) mixed sand-bentonite, (c) fine sand-kaolinite, (d) fine sand-illite, (e) medium sand-sepiolite, (f) medium sand-attapulgite mixtures.

Initially and when the sand content is less than 20%, the bulk thermal conductivity of the soils is dominated by the conductivity of the clay as the sand particles are distributed throughout the sample and are not in contact with each other. As the sand content is increased, the sand particles become closer together until they come in contact. At that point, the thermal conductivity of the soil mixture will be controlled by the conductivity of sand and clay that fills the pores between the sand particles. Because the sand is mainly composed of quartz minerals that have a higher thermal conductivity in comparison to those of the clay minerals, i.e. the thermal conductivity of quartz is about 3 times that of most clay minerals, the bulk thermal conductivity increases. This is shown for all mixtures with a sand content less than 80%. Increasing sand content increases the thermal conductivity of the soil until it is dominated by the sand conductivity alone as the clay grains have very little effect. This results in a nonlinear relationship between thermal conductivity and sand content.

The hydraulic conductivity of composite soils is shown to be a function of the matrix void ratio for matrix dominated composite soils and the intergranular void ratio for clast dominated composite soils. This concept has been extended to thermal conductivity as shown in Figure 5.5 and Figure 5.6.

Figure 5.5 shows that an increase in clay content leads to a reduction in thermal conductivity which is expected since the thermal conductivity of clay particles is less than that for sand particles. It also shows that an increase in the porosity that determined from the matrix void ratio, i.e. an increase in water content, leads to a reduction in thermal conductivity. This is consistent with the fact that the thermal conductivity of water is less than those for the soil particles. However, there is no simple relationship between thermal conductivity and the porosity based on the matrix void ratio.

Figure 5.6 shows that an increase in the porosity that determined from the intergranular void ratio leads to a reduction in thermal conductivity but there is no simple relationship between them. The increase is due to the reduction in sand content associated with an increase in intergranular void ratio.

The void ratio influences the flow of water and heat through soils but thermal conductivity is influenced by the thermal conductivity of the amount and type of soil particles whereas hydraulic conductivity is effected only by the type of clay particles. The thermal conductivity depends on the volume fraction of each constituent of the soil and their thermal conductivity, which means that it will be a function of the global void ratio and not the matrix or intergranular void ratios as these figures show.

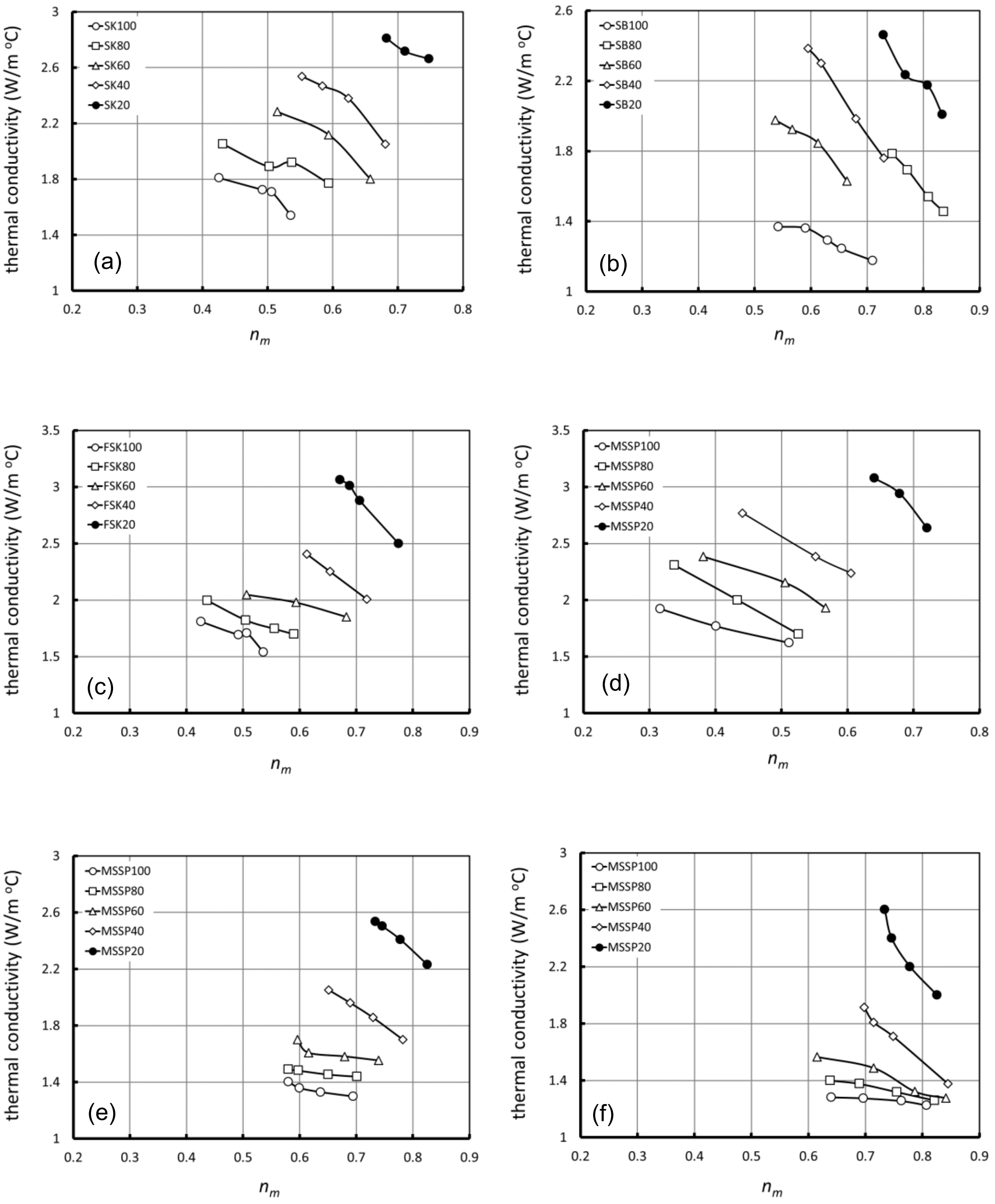


Figure 5.5: The variation of thermal conductivity with porosity (n_m) based on the matrix void ratio in (a) mixed sand-kaolinite, (b) mixed sand- bentonite, (c) fine sand-kaolinite, (d) fine sand-illite, (e) medium sand-sepiolite, (f) medium sand-attapulgite mixtures

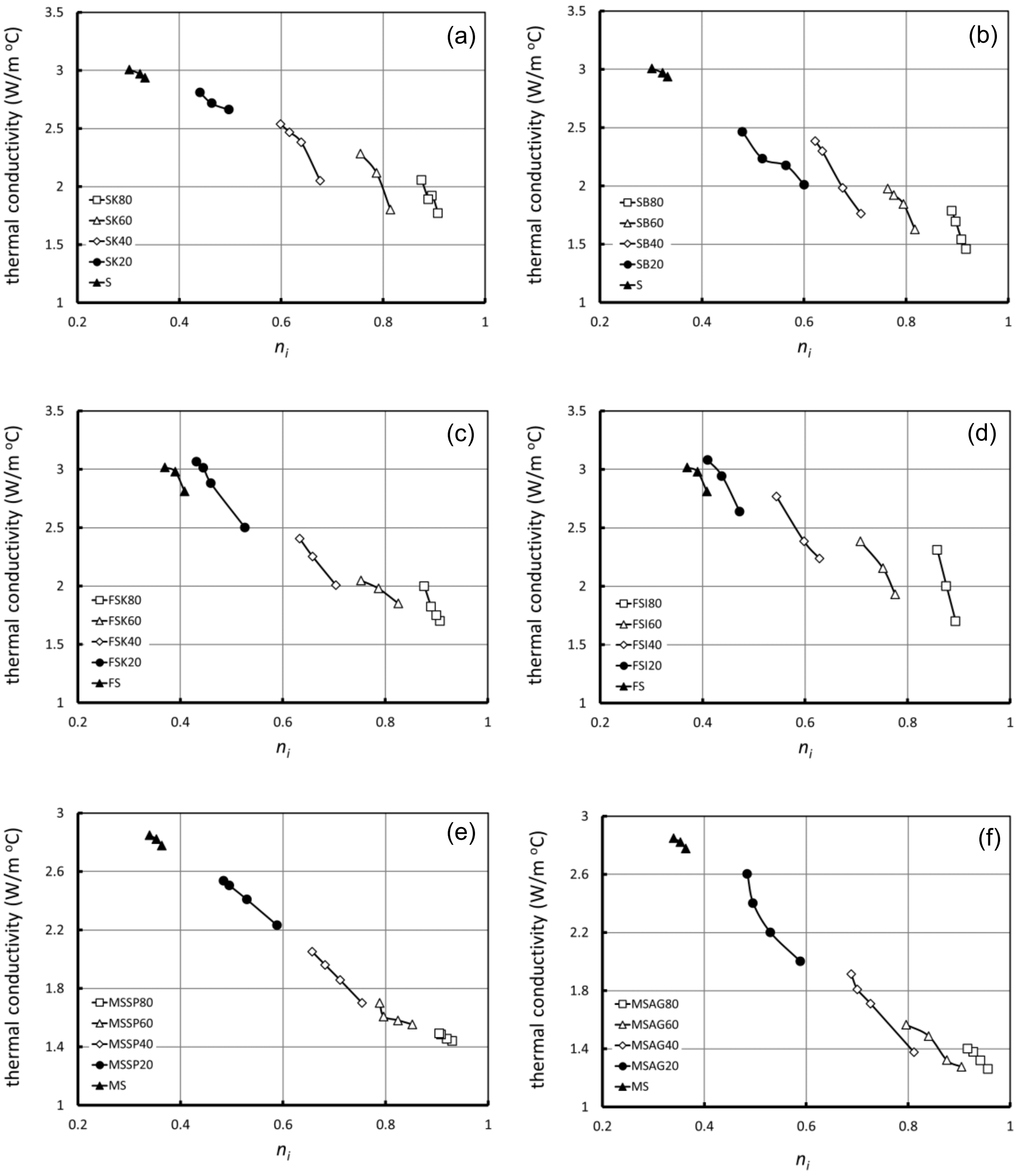


Figure 5.6: The variation of thermal conductivity with porosity (n_m) based on the intergranular void ratio in (a) mixed sand-kaolinite, (b) mixed sand- bentonite, (c) fine sand-kaolinite, (d) fine sand-illite, (e) medium sand-sepiolite, (f) medium sand-attapulgite mixtures

The thermal conductivity of soils is affected not only by the sand content but could also be affected by the particle size of the sand used. In Figure 5.7, the thermal conductivity is plotted against porosity for the three types of sand (mixed, medium, and fine sand). At a certain porosity, the thermal conductivity of mixed sand is slightly higher than that of medium and fine sands. This can be attributed to the fact that the mean size of particles in mixed sands (= 0.69 mm) is higher than that of medium sand with 0.45 mm and fine sand with 0.225 mm which is responsible for the particle structural arrangements and their number of contact points which contribute to heat transfer. Note that the details of the sands used have been described in Chapter Three, section 3.2. This suggests that as the mean particle size of sand increases, the volume of sand particles per unit increases, the soil's porosity decreases, and the resistance to heat flow decreases, and therefore, the thermal conductivity increases. This is consistent with the observation of Midttømme and Roaldset (1998) who found that the thermal conductivity of Vatne quartz and Ottawa sand increases when their particle size increases.

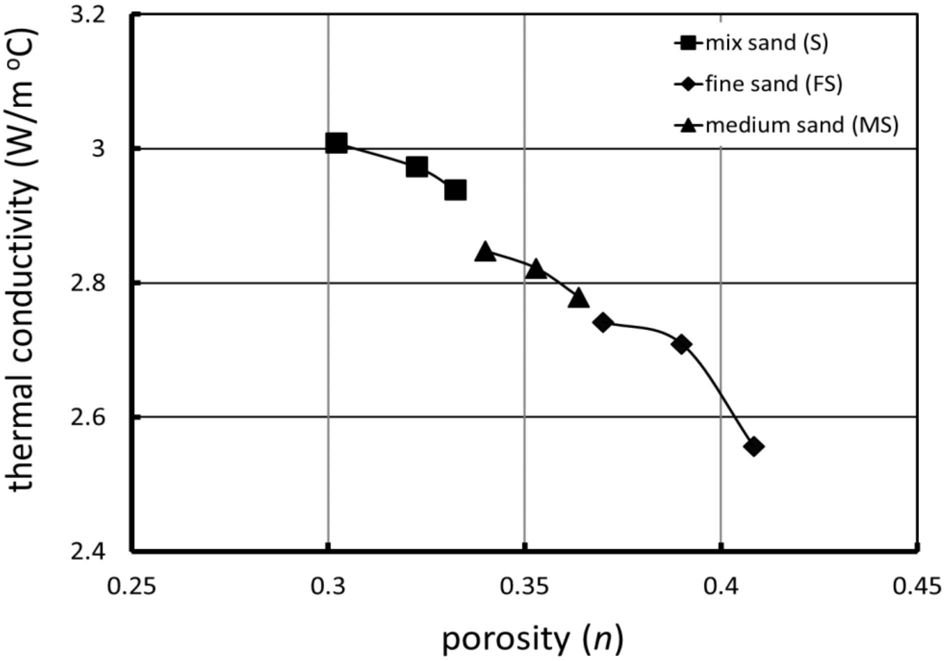


Figure 5.7: The effect of the mean sand particle size on the thermal conductivity

5.3.1.3 Clay mineralogy

Figure 5.3 shows that the clay type has an effect on a soil's thermal conductivity and, since the thermal conductivity of clay is less than that of sand, the clay content has an effect on a soil's thermal conductivity.

Figure 5.8 compares the thermal conductivity of five clays; kaolinite, bentonite, illite, sepiolite and attapulgite clay plotted against their porosity. It can be seen that the relationship between the thermal conductivity and porosity varies between the types of clays. The bulk thermal conductivity of kaolinite is shown from Figure 5.8 to have the highest values amongst the clays.

To assess the effect of clay minerology on the thermal conductivity further, the change in the thermal conductivity with the liquid limit at different values of porosities is plotted in Figure 5.9. The solid markers refer to thermal conductivity at a porosity of 0.5 which is found from the best fit line from ($k_t - n$) relationship for each clay. Figure 5.9 indicates that as the liquid limit of the soil increases, the thermal conductivity decreases. This can be attributed to the fact that liquid limit of soils has a direct correlation with the specific surface area (Farrar and Coleman, 1967, Muhunthan, 1991) that depends on both size and shape of particles (RÓŻAŃSKI and Stefaniuk, 2016). The smaller the particle sizes, the higher the surface area and the higher the liquid limit. Since the particle size has a direct relationship with the thermal conductivity, a soil with a higher liquid limit and smaller particle size will exhibit a lower thermal conductivity.

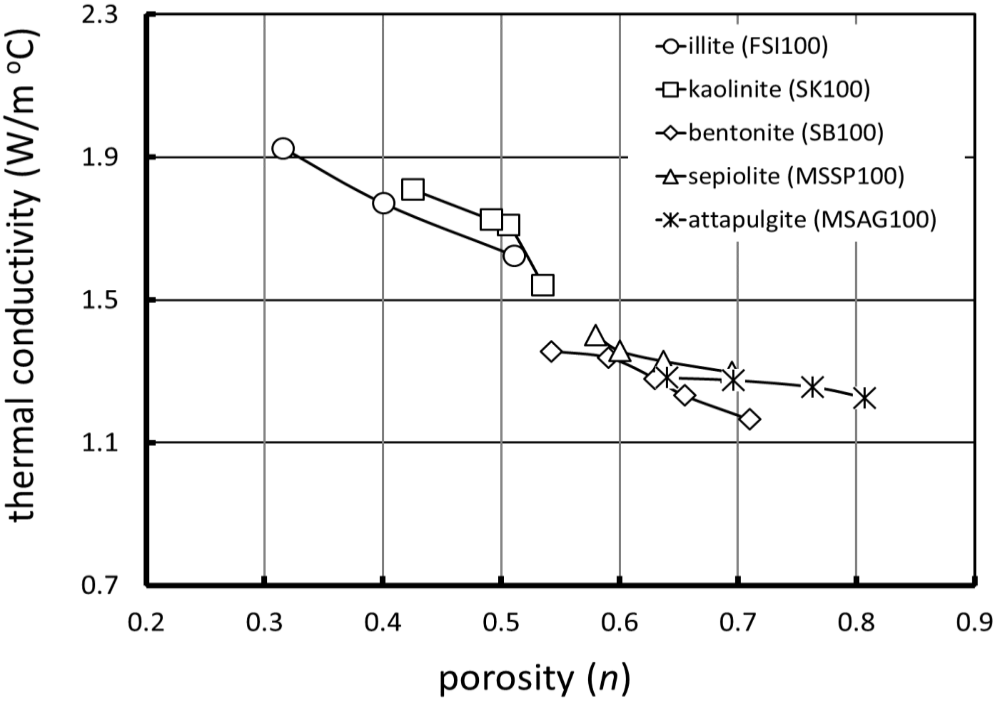


Figure 5.8: Thermal conductivity vs porosity of kaolinite, bentonite, illite, sepiolite and attapulgite clay.

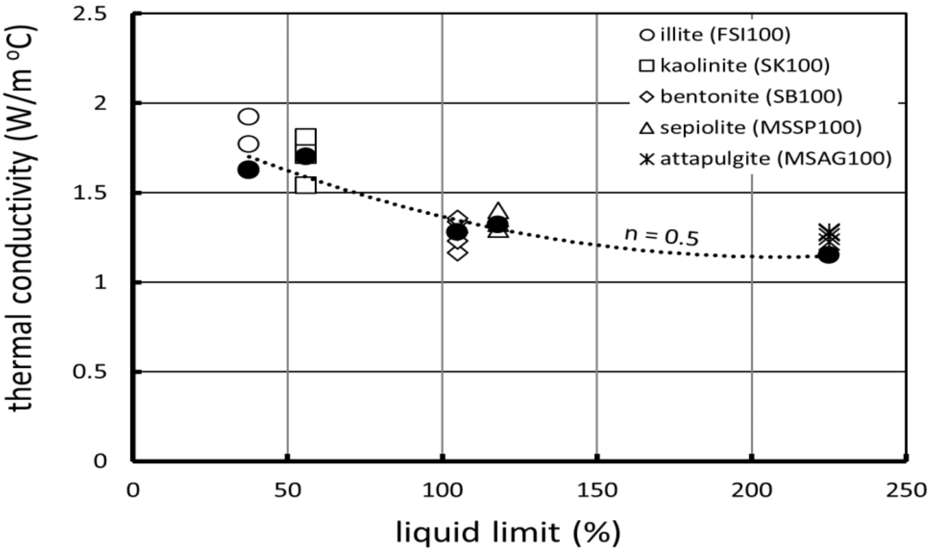


Figure 5.9: The effect of clay minerology on the thermal conductivity of soils

5.3.2 Effect of physical properties on thermal conductivity

In this section, the relationships between the bulk thermal conductivity of composite soils and the water content and dry density are presented.

5.3.2.1 Water content

Since the thermal conductivity of water is less than that of soil particles, it would be expected that an increase in water content leads to a reduction in thermal conductivity of the saturated soils. Figure 5.10 shows the relationship between the thermal conductivity and water content of saturated composite soils (mixed sand-kaolinite, mixed sand-bentonite, fine sand-kaolinite, fine sand-illite, medium sand-sepiolite, and medium sand-attapulgite mixtures). It is obvious that as the water content increases, the value of the thermal conductivity decreases. This can be attributed to the fact that in saturated soils, the heat transfers essentially through the higher conductive solid particles and their contact points, and then through water contained in the pore spaces. Consolidating the soil reduces the water content thus increasing the effect of the solid particles which have a higher thermal conductivity. As the amount of solids per volume unit is increased, the value of thermal conductivity is increased. Figure 5.10 also confirms that for all composite soil mixtures, as the sand content increases, the thermal conductivity increases but the relationship depends on the type of clay. In mixed sand-kaolinite, fine sand-kaolinite, fine sand-illite mixtures, the curves are almost parallel whereas in mixed sand-bentonite and medium sand-attapulgite mixtures, data fall within a narrow band. This could be due to the clay minerology that affects the initial condition of the mixture and the particle arrangement and density. The initial water content of kaolinite and illite is lower than that for the other clays due to their lower liquid limit (low plasticity clays) and addition of any sand can significantly increase the density and establish the particle contacts which therefore increases the thermal conductivity of the mixtures.

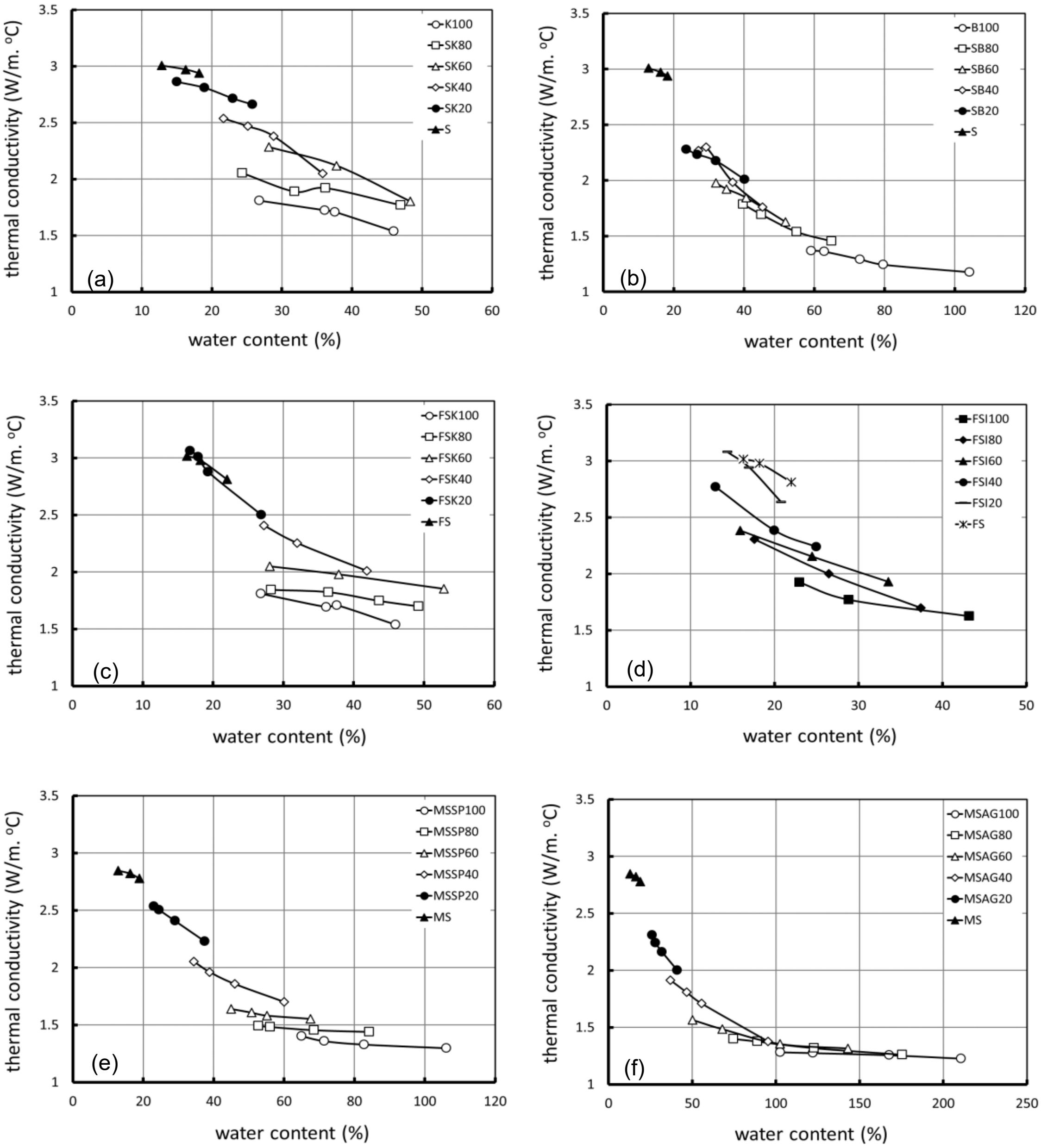
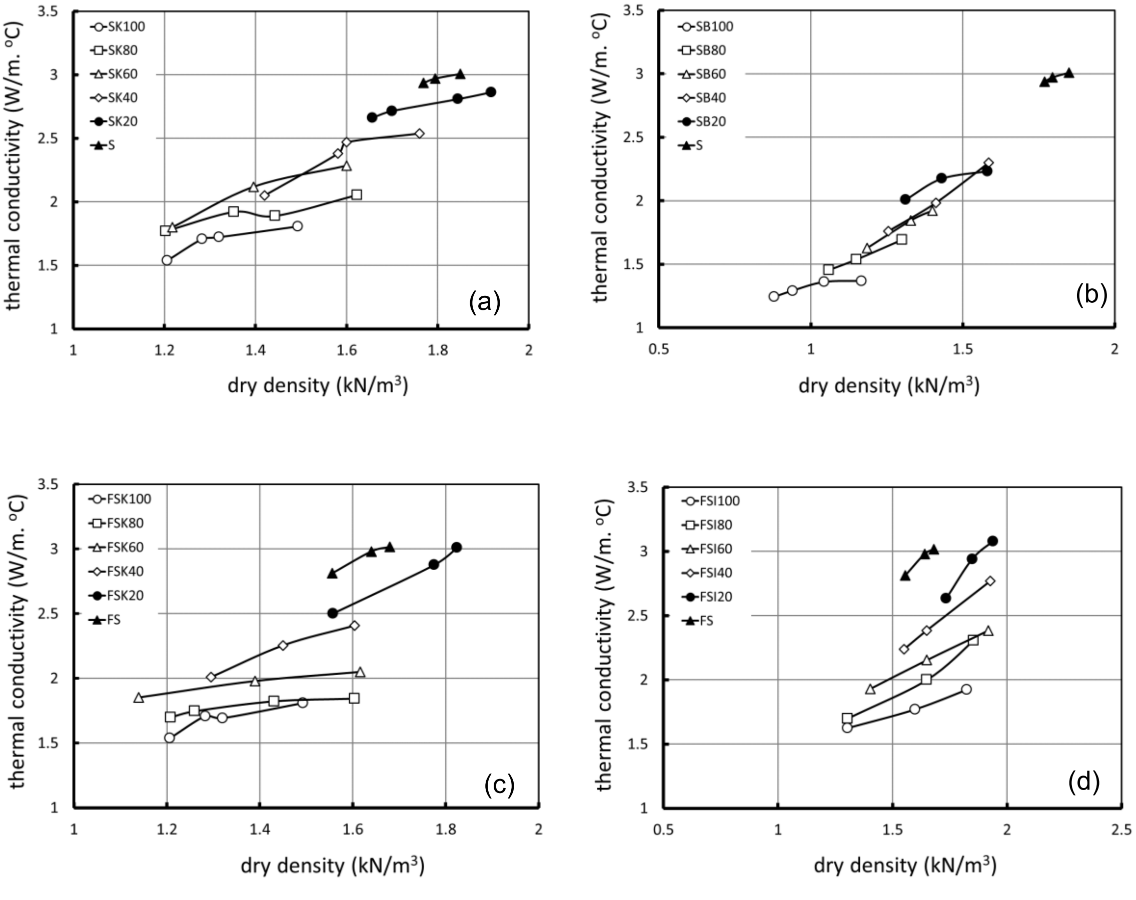


Figure 5.10: The variation of thermal conductivity with water content of: (a) mixed sand-kaolinite, (b) mixed sand-bentonite, (c) fine sand-kaolinite, (d) fine sand-illite, (e) medium sand-sepiolite, (f) medium sand-attapulgite mixtures.

In the mixtures with bentonite and attapulgite, the initial high water content and low density could be the reason that the sand content does not have such a great effect at low percentages (less than 40%). This mean that the transitional behaviour in thermal conductivity in composite soils depends not only on the sand content alone but also on the clay mineralogy and the initial conditions.

5.3.2.2 Dry density

As reviewed in chapter two and seen in Figure 5.10 and Figure 5.11, water content and density are the physical parameters that most affect the thermal conductivity of soils. In Figure 5.11, as a soil's dry density increases, the thermal conductivity increases which is due to the increase in solid particles in a unit volume and also in their contact bonds that both contribute to the heat transfer paths in soils. Figure 5.11, also, shows that the increase in thermal conductivity is greater when the soils become dominated by the sand content.



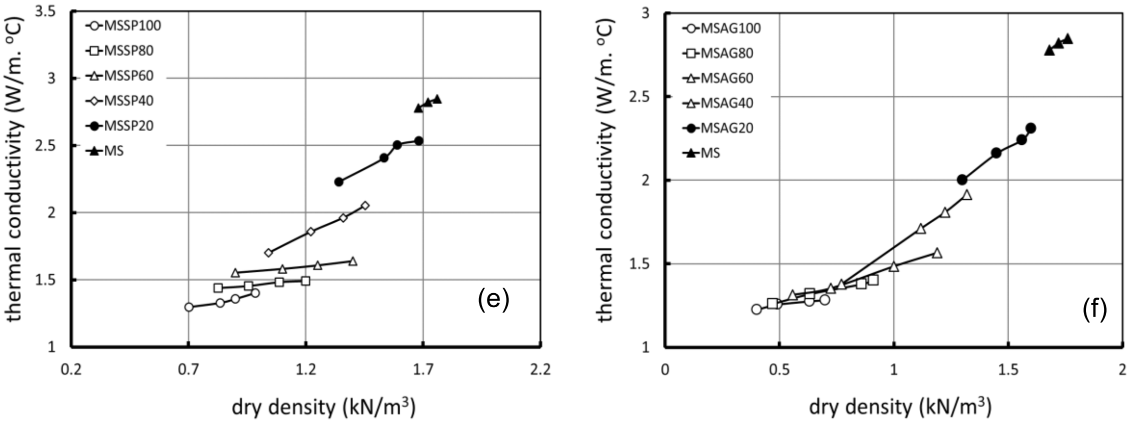


Figure 5.11: The variation of thermal conductivity with dry density of: (a) mixed sand-kaolinite, (b) mixed sand-bentonite, (c) fine sand-kaolinite, (d) fine sand-illite, (e) medium sand-sepiolite, (f) medium sand-attapulgite mixtures.

5.3.3 Use of published thermal models with composite soils

As discussed in chapter two, section 2.6.4, Johansen's model has been assessed (e.g. Sass et al., 1971, Farouki, 1982, Brigaud and Vasseur, 1989, Midttomme and Roaldset, 1998, Côté and Konrad, 2005a,b, Côté and Konrad, 2007) to be the most widely accepted predictive model for estimating the bulk thermal conductivity of soils (k_t),which is in the form of:-

$$k_t = \left(k_{sat} - k_{dry}\right) * K_e + k_{dry} \qquad (5.1)$$

For fully saturated unfrozen soils, Johansen's formula can be reduced to:

$$k_t = k_{sat} = k_w^{x_w} k_s^{x_s} \qquad (5.2)$$

Where k_t is the bulk thermal conductivity (W/m °C), k_w, k_s are the thermal conductivity of water and solid particles, respectively (W/m °C), x_w, x_s are the volume fractions of water and solid particles in the soil matrix. This model was used to estimate the value of bulk thermal conductivity of saturated composite soils used in this research. The thermal conductivity of water (k_w) was taken as (0.57 W/m. °C) and the thermal conductivity of the solid particles (k_s) was determined using the work of Gemant and then by the equation of Johansen described below.

Gemant correlated thermal conductivity of solid particles (k_s) with the percentage of clay (C_m) contained in soil's solids:-

$$k_s = 5.84 - 3.3C_m \qquad (5.3)$$

Where C_m represents the percentage by weight of clay in the solid phase of the soil, column 4 in Table 5.1. Figure 5.12 and 5.13 show comparisons between the measured values of the bulk thermal conductivity of composite soils and those estimated by equ. 5.2, and equ 5.3. Equ 5.2, using Gemant's constants, underestimates the values with Root Mean Square Error (*RMSE*) of 0.31 suggesting that the constants of Gemant, and, possibly, the fact that it is only based on the clay content, is not appropriate to estimate the bulk thermal conductivity.

Johansen's method is based on the quartz content of a soil to determine k_s in the form of:

$$k_s = k_q^{x_q} k_o^{1-x_q} \qquad (5.4)$$

Where k_q, k_o are the thermal conductivity of quartz and other minerals, respectively; x_q is the fraction of quartz in the soil-solid phase. Johansen assumed that the thermal conductivity of quartz equals to (k_q = 7.7 W/m °C), while the thermal conductivity of all other soil minerals equals to (k_o = 2 W/m °C except in case of $x_q < 0.2$, k_o = 3 W/m °C).

Although determining the thermal conductivity of solid particles, k_s, by Johansen's equation (equ. 5. 4) gives a better estimate in Figure 5.13, specifically for composite soils of high sand content, there is still a discrepancy with *RMSE* = 0.26. This may be because of the unrepresentative values of the thermal conductivity of solid particles that were used for all clays (2 and 3 W/m ^{o}C) and sands (7.7 W/m ^{o}C). It was also assumed that the thermal conductivity of the sand particles was the same as that of quartz ignoring the fact the thermal resistance between the sand particles reduces the thermal conductivity compared to that of solid quartz.

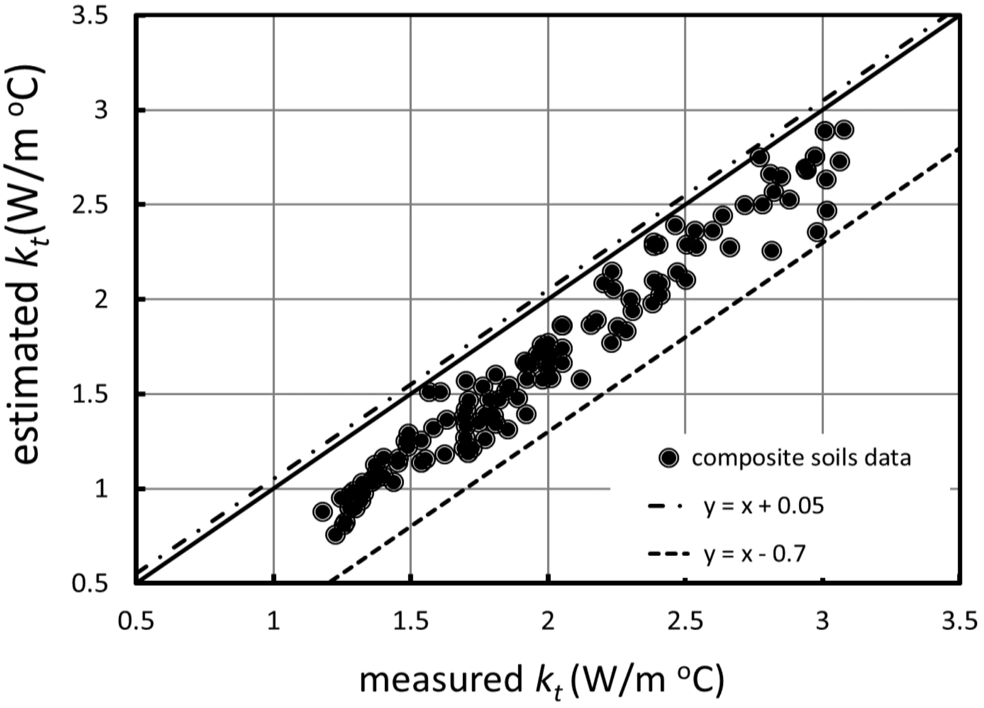


Figure 5.12: A comparison between the estimated and measured values of the thermal conductivity using equ. 5.2 & 5.3.

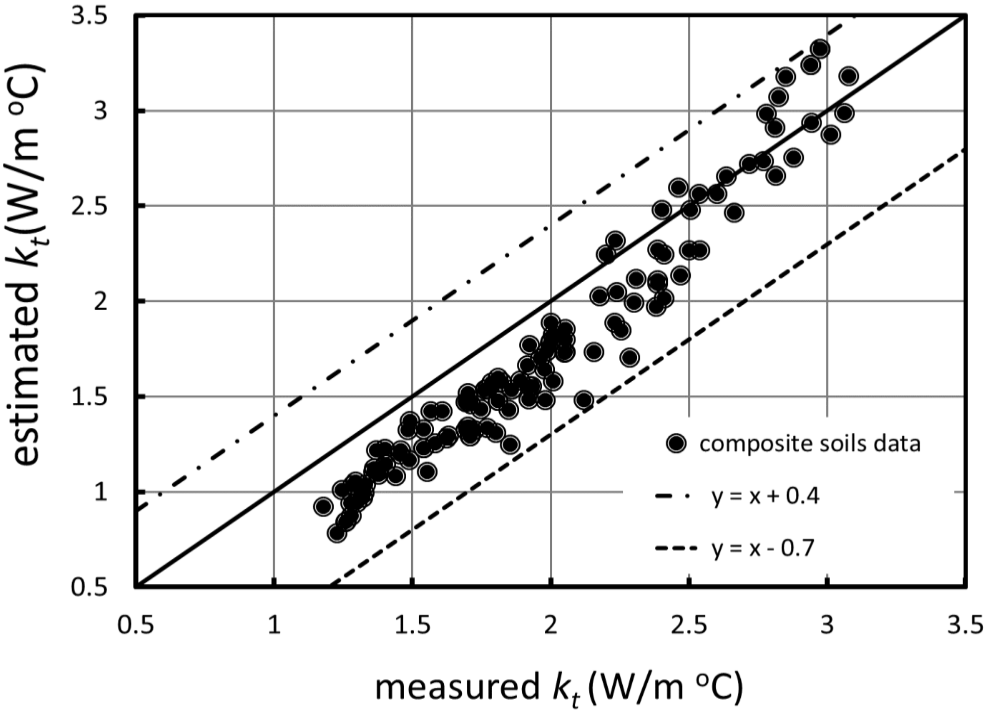


Figure 5.13: A comparison between the estimated and measured values of the thermal conductivity using equ. 5.2 & 5.4

5.3.4 Estimating thermal conductivity from soil composition

The estimated values of the thermal conductivity shown in Figures 5.12 and 5.13 are not in very good agreement with the measured values because:

- Germant's constants are not universal for all type of composite soil mixture and this method captures only clay content ignoring the effect of sand particle size and clay mineralogy.
- Johansen's method for solid particles is based only on the quartz content using fixed vales for all types of clays and sands which may be unacceptable neglecting the effect of particle size and clay mineralogy.

To improve the accuracy of the results and to decrease the discrepancy between the estimated and measured values, a more representative model is introduced, in which the solid phase in Johansen's model (k_s) is separated into two solid phases, clays and sands, taking into account their individual volume fractions in the whole soil mass, as follows:

$$k_t = k_w^{x_w} k_{clay}^{x_{clay}} k_{sand}^{xsand} \qquad (5.5)$$

Where:

k_{clay} = the thermal conductivity of clay-forming minerals (W/m °C),

k_{sand} = the thermal conductivity of sand-forming minerals (W/m °C),

x_w = volumetric fraction of water in the whole soil (porosity)

x_{clay} = volumetric fraction of clay in the whole soil

x_{sand} = volumetric fraction of sand in the whole soil.

It follows that the volumetric fraction of clay (x_{clay}) and sand (x_{sand}) in the whole soil can be determined from the percentage by weight of clay and sand and dry density or porosity of the soils:-

$$x_{clay} = \frac{V_{clay}}{V_T} = \frac{C_m\,\gamma_d}{G_c\,\gamma_w} = \frac{C_m\,G_T(1-n)}{G_c}, \qquad (5.6)$$

$$x_{sand} = 1 - (x_{clay} + x_{water}) \qquad (5.7)$$

Where: C_m = percentage by weight of clay in the solid phase of the soil (as % clay content), column 4 in Table 5.1.

γ_d = dry unit weight of soils (kN/m^3),

γ_w = unit weight of water (kN/m^3),

G_c = specific gravity of clay,

G_T = specific gravity of the composite soil mixture, column 6 in Table 5.1.

To estimate the bulk thermal conductivity of composite soils using this model (equ. 5.5), the thermal conductivity of clay- and sand- minerals (k_{clay}, k_{sand}) should be known. If equ 5.5 is correct, then it should be possible to determine the equivalent thermal conductivity of clay and sand (k_{clay} and k_{sand}) by back analysing the tests on pure clays and clean sands. The values of thermal conductivity of clay- and sand- minerals are provided in Table 5.8.

Table 5.8: The effective thermal conductivity of sand and clay- minerals, k_{clay}, k_{sand}

Soils		k_{clay}, k_{sand} (W/m °C)
Clays	Kaolinite	3.6
	Bentonite	3.3
	Illite	3.0
	Sepiolite	3.5
	Attapulgite	3.4
Sands	Fine sand	7.0
	Medium sand	7.1
	Mixed sand	7.4

Using the back figured values of k_{clay} and k_{sand} and the calculated volumetric fractions (x_{clay}, x_{sand}) in the whole soil mass, the bulk thermal conductivity of other sand-clay mixtures was determined using equ. 5.5. The estimated and measured values of the bulk thermal conductivity of all composite soils are shown in Figure 5.14 which shows that using the equivalent thermal conductivity of the clay and sand particles and equ. 5.5 provides a better estimate of the thermal conductivity of the soil mass with *RMSE* of 0.18 compared to that shown in Figure 5.12 or Figure 5.13.

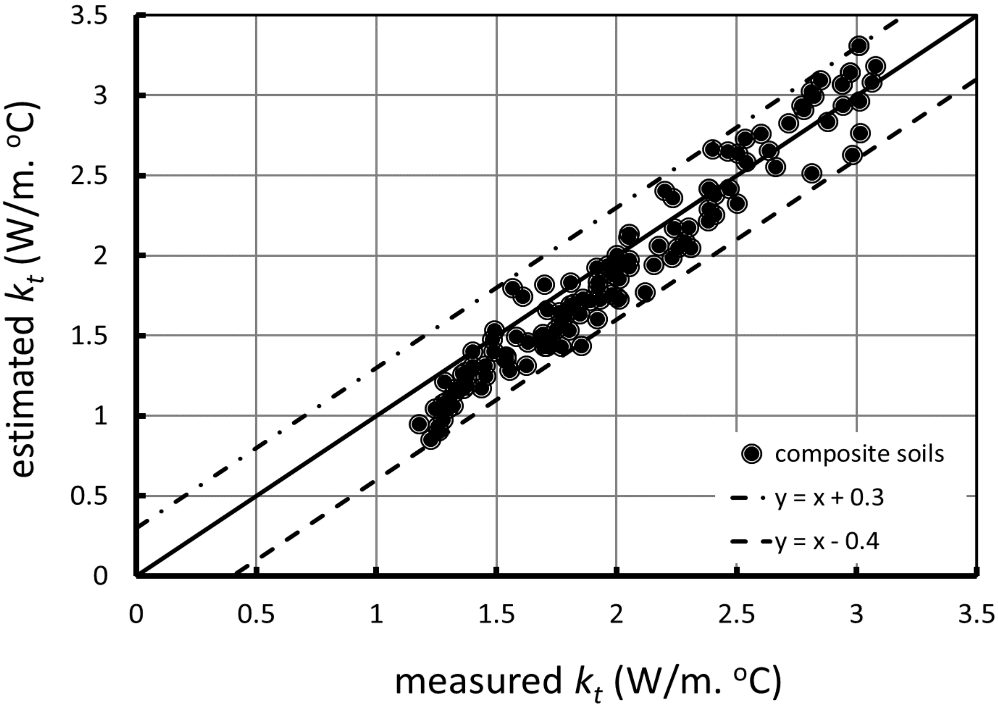


Figure 5.14: A comparison between the estimated and measured values of the thermal conductivity using equ 5.5

5.4 Summary

The results for the thermal conductivity of a wide range of composite sand-clay mixtures were presented and analysed. It was shown that at a constant heat flux, the increase in temperature in sands generally exceeded that for clays and the time needed to reach the maximum temperatures was shorter for sands than for clays.

An increase in sand content, soil density, a decrease in water content leads to an increase in thermal conductivity of the composite soils because the thermal conductivity of the sand particles exceeds that of clay minerals and water. It is not only the sand content that control the thermal conductivity, but it is also the particle size of the sand used in that as the mean particle size of sand increases, the volume of sand particles per unit increases and the resistance to heat flow decreases, and therefore, the thermal conductivity increases. The transitional behaviour from clay-dominated to sand-dominated composite soils in thermal conductivity was not so well defined but depends on the sand content, particle size, the clay mineralogy and the initial conditions. Among clays, kaolinite was seen to have the highest thermal conductivity values which could be due to the effect of clay mineralogy.

The measured thermal conductivity data of composite soils was compared with those predicted from common thermal conduction models to show that the models either underestimate the values or provide reasonable estimate with some discrepancy. A new model for composite soils was established based on the thermal properties of the soil's constituents; sand, clay, and water.

Chapter 6

Electrical Conductivity Results of Composite Soils

6.1 Introduction

Tests results for electrical conductivity of composite sand-clay soils are presented. The effect of sand/clay content and the type of clay mineralogy on the overall soil electrical conductivity are highlighted. The impact the pore water conductivity and the clay surfaces have upon the overall soil electrical conductivity are investigated. Relationships between the overall electrical conductivity with water content and porosity of composite soils are presented.

The measured data of electrical conductivity on composite soils were compared to those predicted from common electrical models and new models are introduced to account for the effect of high clay content at low salinity.

6.2 Composite soils used for electrical tests

Electrical conductivity measurements were carried out on soils composed of clay and sand mixtures in proportions by weight of 0, 20, 40, 60, 80, and 100%. The types of clays and sands used are exactly the same as those used in the thermal conductivity tests, that are collectively presented in Table 3.1. All mixtures of composite soils used for electrical conductivity tests along with their index and electrochemical properties are presented in the Table 6.1. The index properties of all mixtures were determined following the same procedures used in chapter five.

6.2.1 Physical-chemical properties of composite soils

6.2.1.1 Specific surface area

The specific surface area test was carried out using the proposal of Santamarina et al. (2002). The methylene blue solution (MB) test was used to determine the surface area of composite soils.

Table 6.1: Composite soils used for electrical conductivity measurements

Groups	Samples	Symbol	Clay content (C_m %)	Specific gravity (G_T)	Liquid limit (I_L %)	Plastic limit (I_P %)	Plasticity index (PI %)	Activity (A)	Specific area (m^2/g)	*CEC* (meq/g)	*pH** From specification
1	Kaolinite	SK100	100	2.60	56.0	33.0	23.0	0.68	21.36	0.044	5.0
	Mixed sand - Kaolinite	SK80	80	2.61	48.1	29.0	19.2	0.72	17.57	0.033	
	Mixed sand - Kaolinite	SK60	60	2.62	38.4	23.7	15.0	0.78	12.74	0.024	
	Mixed sand - Kaolinite	SK40	40	2.63	27.8	16.4	11.5	0.85	8.20	0.020	
	Mixed sand - Kaolinite	SK20	20	2.64	17.2	-	-	-	4.48	0.010	
	Mixed sand	S	0	2.65	-	-	-	-	0.04	0.001	
2	Fine sand - kaolinite	FSK80	80	2.60	48.2	28.8	19.4	0.71	17.22	0.030	
	Fine sand - kaolinite	FSK60	60	2.61	38.7	23.0	15.7	0.77	12.40	0.022	
	Fine sand - kaolinite	FSK40	40	2.62	27.9	15.4	12.5	0.84	8.27	0.017	
	Fine sand - kaolinite	FSK20	20	2.63	17.9	-	-	-	4.48	0.010	
	Fine sand	FS	0	2.63	-	-	-	-	0.03	0.001	
3	Calcium bentonite	SB100	100	2.55	105.0	48.0	57.0	1.97	444.35	0.673	8.5
	Mixed sand - Bentonite	SB80	80	2.57	87.2	41.6	46.3	2.01	358.23	0.582	
	Mixed sand - Bentonite	SB60	60	2.59	66.9	30.1	37.4	2.08	263.16	0.425	
	Mixed sand - Bentonite	SB40	40	2.61	46.9	22.7	24.6	2.13	170.16	0.294	
	Mixed sand - Bentonite	SB20	20	2.63	26.7	-	-		89.56	0.147	
4	illite	FSI100	100	2.67	37.6	20.0	17.6	0.41	82.67	0.130	7.0
	Fine sand - illite	FSI80	80	2.66	31.5	16.2	15.3	0.44	63.38	0.090	
	Fine sand - illite	FSI60	60	2.65	26.0	13.1	12.9	0.48	49.60	0.060	
	Fine sand - illite	FSI40	40	2.64	20.5	-	-	-	35.13	0.045	
	Fine sand - illite	FSI20	20	2.63	15.2	-	-	-	16.53	0.020	
5	Sepiolite	MSSP100	100	2.30	118.0	86.5	31.5	1.17	210.12	0.277	8.8
	Medium sand - Sepiolite	MSSP80	80	2.38	92.9	69.0	23.9	1.19	174.98	0.228	
	Medium sand - Sepiolite	MSSP60	60	2.46	70.0	51.2	18.8	1.23	124.00	0.155	
	Medium sand - Sepiolite	MSSP40	40	2.54	48.0	35.5	12.5	1.25	86.80	0.107	
	Medium sand - Sepiolite	MSSP20	20	2.61	25.1	-	-	-	46.16	0.049	-
	Medium sand	MS	0	2.64	-	-	-	-	0.02	0.001	
6	Attapulgite	MSAG100	100	2.08	225.0	126	99.0		151.56	0.233	10
	Medium sand - Attapulgite	MSAG80	80	2.20	187.0	105	82.0		125.38	0.175	
	Medium sand - Attapulgite	MSAG60	60	2.33	136.0	80.2	55.8		90.94	0.131	
	Medium sand - Attapulgite	MSAG40	40	2.50	92.0	50.1	41.9		55.11	0.097	
	Medium sand – Attapulgite	MSAG20	20	2.58	50.0	-	-	-	30.31	0.039	

*S= mixed sand; FS= fine sand; MS= medium sand; K= kaolinite; B= bentonite; I= illite; SP= sepiolite; AG= attapulgite

*pH: taken from company's specification.

To prepare the methylene blue solution (MB), 1 gm dry powder of methylene blue dye was mixed with 200 mL deionized water, Figure 6.1a. The solution of MB was added gradually with an increment of 0.5 mL to a soil suspension, Figure 6.1c (prepared from 10 gm of dry soil with 30 mL of deionized water, Figure 6.1b) and then a small drop was taken from the mixture and placed on a screen of filter paper, Figure 6.1d. The process was continued until the soil on the filter paper was surrounded by a blue halo.

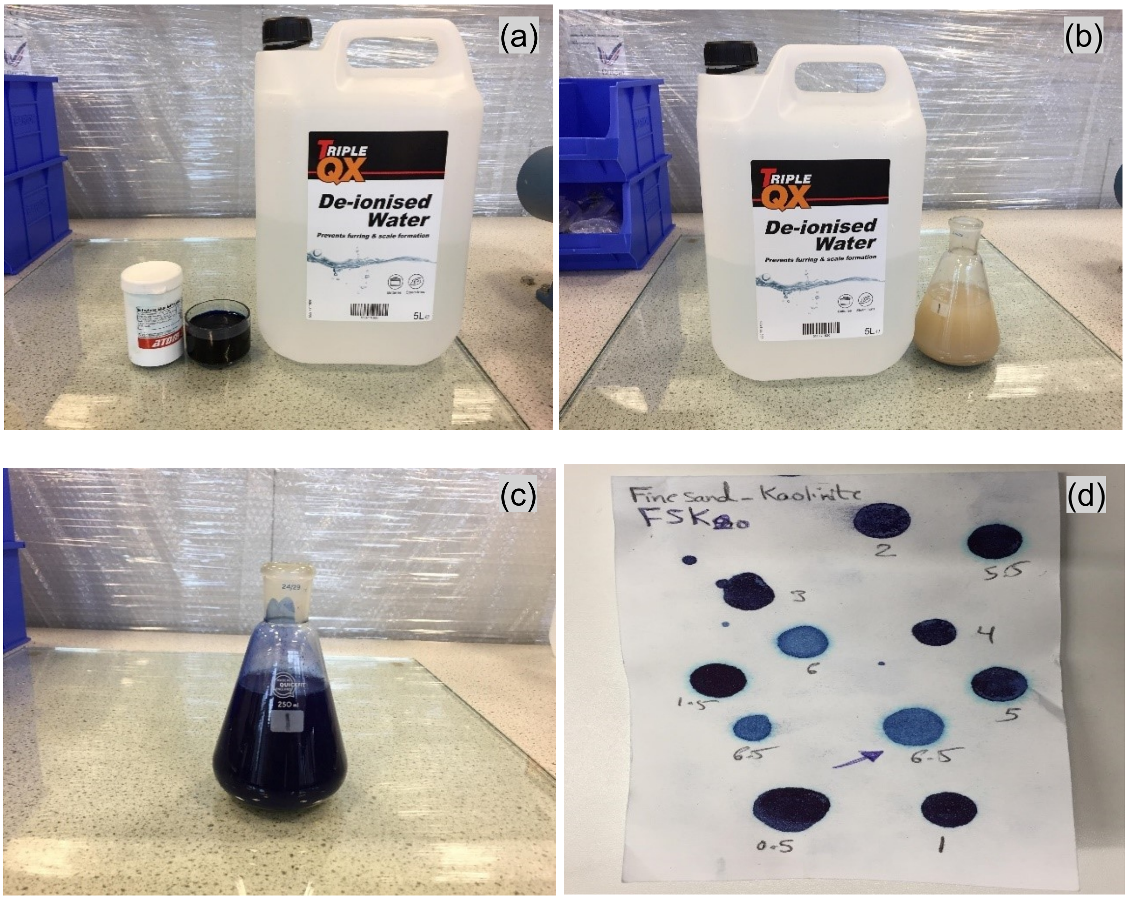


Figure 6.1: Photographs showing the process of determination of specific surface area (A_s) of composite soils

The surface area was determined by:

$$A_s = \frac{1}{319.87}\frac{1}{200}(0.5N) * 130 * 6.02 * 10^{22} \tag{6.1}$$

Where A_s is the surface area in m^2/g, and N is number of MB increments. The results of the surface area of composite soils are presented in Figure 6.2. As the surface area (A_s) is strongly related to the amount of clay particles, the relationship between A_s and clay content as percentages was established in Figure 6.2. This figure shows that there is a direct relationship between surface area and clay content for all composite soil mixtures in that an increase in the clay content implies an increase in the surface area. At a certain clay content, the specific surface area of bentonite is higher than that for all other clays and kaolinite has the lowest value among the five clays The specific surface area of sands, at clay content of zero, is very small and, in most cases, it can be neglected. Figure also confirms that the specific surface area of the mixtures is a function of the amount and type of clays in the mixtures.

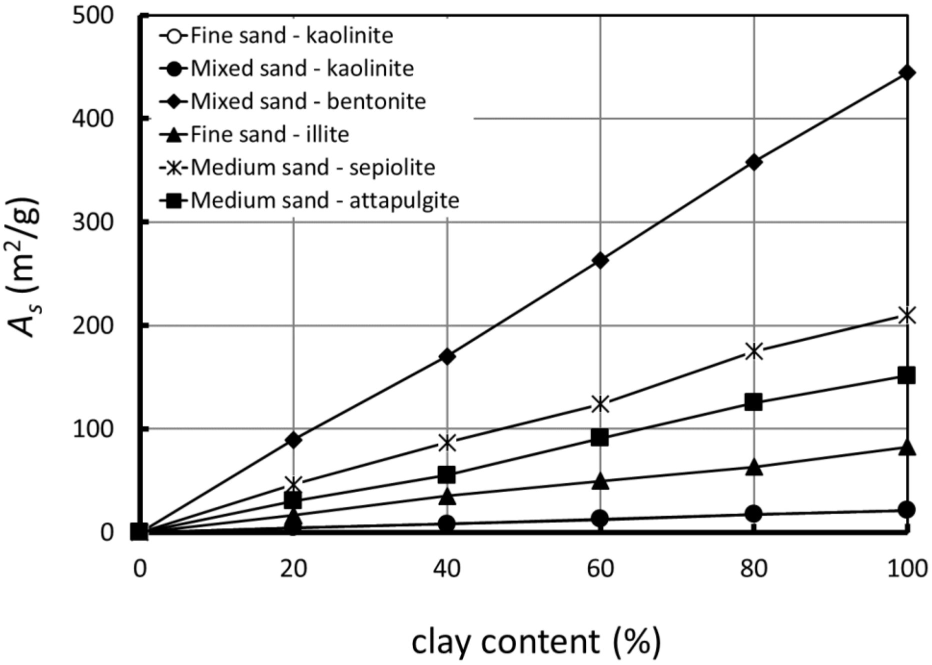


Figure 6.2: The relationship between the specific surface area and clay content

6.2.1.2 Cation exchange capacity

Cation exchange capacity (*CEC*) expresses the total capacity of a soil to retain exchangeable cations on the surfaces of the solid particles. It is of a paramount significance in the interpretation of the clay surface conductivity, particularly in clay-rich composite soils (Waxman and Smit, 1968; Revil et al., 1998). *CEC* of soils shows a considerable variation relying on composition and particle size distribution (i.e. for clean sands, *CEC* < 0.002; and for pure clays, *CEC* = 0.03 -1.5 meq/g).

Different methods and test procedures, based on various physico-chemical assumptions, have been proposed to determine the *CEC* (i.e. those by Ammonium Acetate (Chapman, 1965); nitrogen adsorption (Brunauer et al., 1938); barium chloride (Hendershot and Duquette, 1986); compulsive exchange (Gillman and Sumpter, 1986); methylene blue (Cokca and Birand, 1993). Among all methods, the methylene blue (MB) is the easiest and simplest method to determine the CEC of soils. Yukselen and Kaya (2008) carried out an investigation to check the applicability of the MB method and showed that such a method can be used effectively for determining the *CEC* of a wide range of soils. Wang et al. (1996), Soon (1988), and Taylor (1985) stated that the values obtained by MB method are, in general, lower than those of the Ammonium Acetate method.

Given the importance of *CEC* in the interpretation of surface conduction of soils, a number of attempts was made to correlate the *CEC* with the more simple physical properties of the soils (Farrar and Coleman, 1967, Curtin and Smillie, 1976, Tiller and Smith, 1990, Churchman et al., 1991, Petersen et al., 1996, Yukselen and Kaya, 2006). The majority of these attempts showed that the surface area property (A_s) has the most significant relationship with the *CEC*. For instance, Farrar and Coleman (1967) carried out an investigation on British clayey soils to show that about 91% correlation coefficient exists between *CEC* and surface area (A_s). Similarly, Curtin and Smillie (1976) indicated in their study on Irish soils that there is a significant relationship between the *CEC* and the surface area but not with clay content. According to Yukselen and Kaya (2006), the strength of the (*CEC* - A_s) correlation depends on the test methods used to determine *CEC* and A_s.

The cation exchange capacity (*CEC*) of all composite soil mixtures was determined following the Cokca and Birand (1993) procedures. The methylene blue solution (MB) was prepared by mixing 1 gm dry powder of methylene blue dye with 100 mL deionized water, Figure 6.3a. The solution of *MB* was added gradually with an increment of 0.5 mL to a soil suspension, Figure 6.3c (prepared from 30 gm of dry soil with 200 mL of deionized water, Figure 6.3b) and then a small drop was taken from the mixture and placed on a screen of filter paper, Figure 6.3d. The process was continued until the soil on the filter paper was surrounded by a blue halo and the cation exchange capacity was determined by:

$$CEC = \frac{100}{M} V_{cc} N_{mb} \qquad (6.2)$$

Where *CEC* is the cation exchange capacity (meq/100g), *M* is the mass of the clay sample (g), V_{cc} is the volume of the methylene blue (mL), N_{mb} is the normality of the methylene blue solution (meq/mL).

$$N_{mb} = \frac{mass\ of\ the\ MB\ (g)}{319.87} \cdot \frac{100 - x}{100} \qquad (6.3)$$

Where *x* is the water content of the *MB* as %, and 319.87 is the molecular mass of the *MB.* It should be noted that Satamarina (2002) for the determination of A_s used assumptions similar to that suggested by Cokca and Birand (1993) for *CEC*.

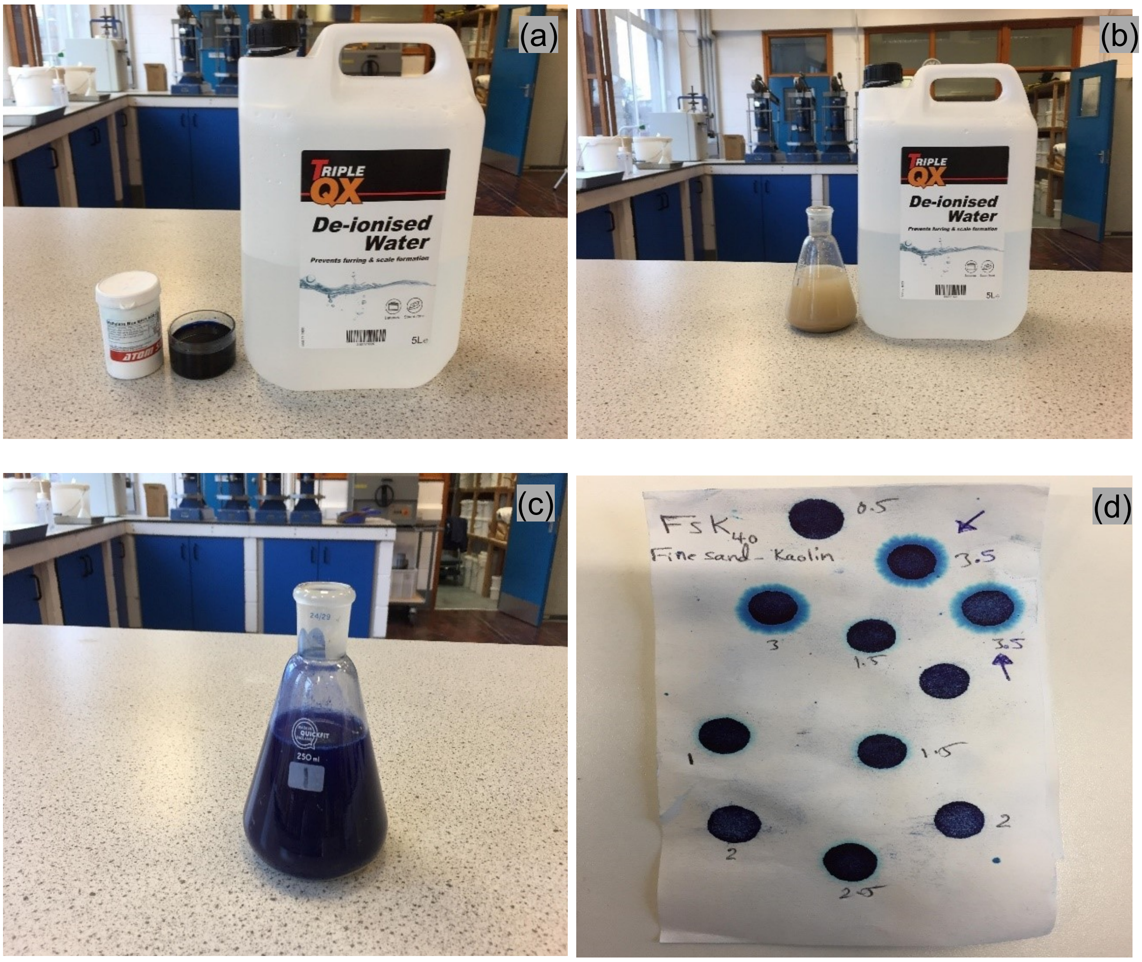


Figure 6.3: Photographs showing the process of determination of cation exchange change (CEC) of composite soils

For the purpose of correlation of the cation exchange capacity (*CEC*) with the soil's physical properties, *CEC* is correlated with liquid limit (I_L), activity (*A*), clay content (%), and specific surface area (A_s) of all composite soil mixtures. Figure 6.4 presents the relationship between *CEC* and I_L for all composite soils. As can be seen, for a specific composite soil mixture, as the liquid limit increases, the *CEC* increases in a nearly linear relation.

Figure 6.5 shows the variation of the *CEC* with clay content for all composite soils. It can be seen that there is a direct linear relationship between the CEC and clay content with different slopes depending on the clay type. It also shows that the trend of the *CEC*-clay content relationship is similar to that between A_s-clay content in Figure 6.2, such that both the cation exchange change, *CEC*, and specific surface area, A_s, depend on clay type and amount in soils suggesting that *CEC* and A_s can be correlated. In Figure 6.6, it can be seen that the correlation between *CEC* and A_s for the composite soils is very significant with a coefficient of 0.99. This may be attributed to the fact both *CEC* and A_s were determined from test methods using similar underlying assumptions that are based on the methylene blue solution. From this, it can be concluded that the cation exchange capacity depends on the amount and type of clays in composite soils and in the absence of data of the cation exchange capacity, *CEC*, of composite soils, it is possible to predict it with some confidence using the specific surface area, A_s.

According to Yukselen and Kaya (2006), the cation exchange capacity can be a good indicator of soil's activity (*A*). For pure clays, the relationship is in good agreement with coefficient of 0.91 (Figure 6.7). However, for all composite soil mixtures, the relation is very poor. This may be because of the fact that increasing sand content (or decreasing clay content) in composite soils have insignificant effect on the activity by decreasing both plasticity index and % clay less than 2um and very significant impact on the cation capacity.

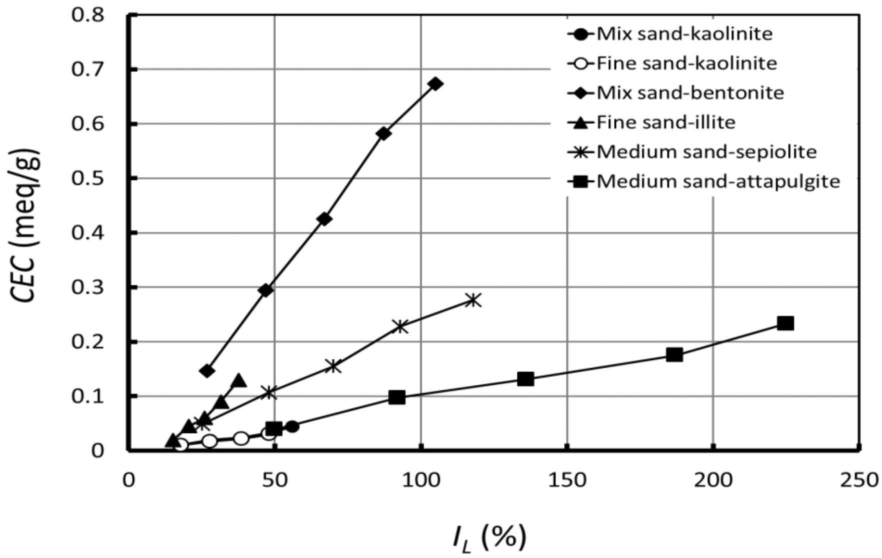


Figure 6.4: The relationship between *CEC* and I_L of composite soils

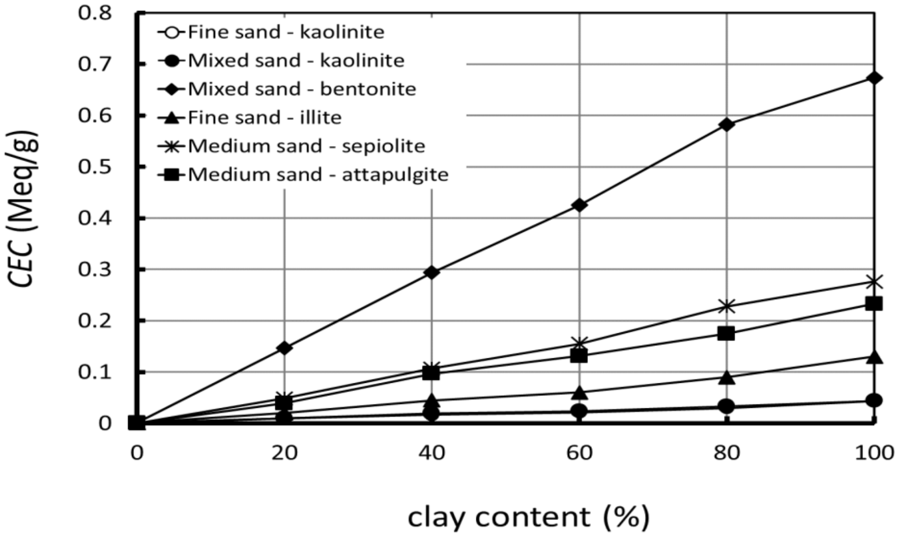


Figure 6.5: The variation of *CEC* with clay content in composite soils

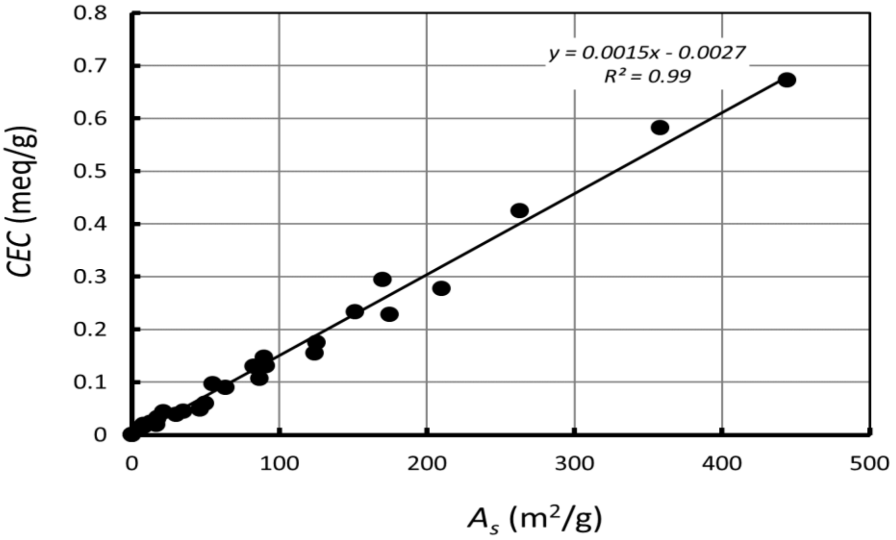


Figure 6.6: The relationship between *CEC* and A_s of composite soils

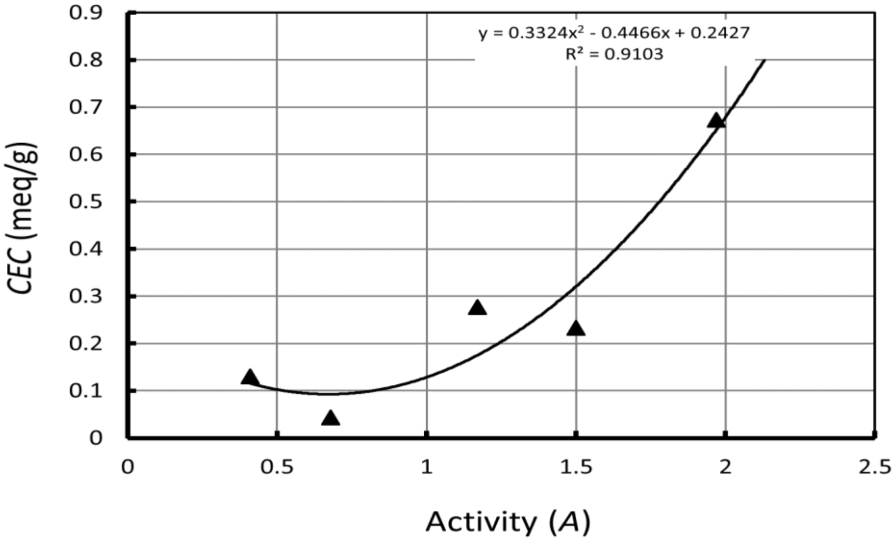


Figure 6.7: The variation of *CEC* with *A* of pure clays

6.2.1.3 pH

The values of *pH* of all clays used were taken from the specifications of the supplier. These values are presented in the Table 6.1.

6.2.2 Electrical conductivity of water used

The electrical conductivity of composite soil-saturating water has an important role in the measurements of the overall soil conductivity. Thus, two types of water were used in the electrical tests, tap and distilled water. The electrical conductivity of water was measured using a sensitive conductivity meter at the University of Leeds and the measured values were (σ_w = 0.0343 S/m) for tap water, and (0.00047 S/m) for the distilled water.

6.3 Electrical conductivity results of composite soils

Thirty seven samples of reconstituted composite soil mixtures were tested to determine the electrical conductivity, following the procedures described in chapter three, and the results obtained are presented here. 32 samples were prepared with tap water and 5 samples with distilled water to assess the effect the pore water conductivity has upon the soil conductivity.

The typical voltage vs current plots for the the saturated pure clays (kaolinite, bentonite, illite, sepiolite, and attapulgite) and for sands (fine, medium and mixed sand), the main materials used to form composite soil mixtures, is shown in Figure 6.8 and Figure 6.9, respectively.

It can be seen from Figure 6.8 and Figure 6.9 that when the voltage is increased, the resulting current passing through the clays and sands increases but the amount of increase depends on the soil type. The slope of the line represents the resistance that is equal to ($R = \Delta V / \Delta I$). Inspection of Figure 6.8 shows that bentonite has the lowest resistance (R ≈ 76 Ohm) to the current flow among clays and kaolinite (R ≈ 957 Ohm) has the highest. This is because bentonite particles have a higher surface area and cation exchange capacity, *CEC* of (444.35 m^2/g, 0.673 meq/g) compared to kaolinite (21.36 m^2/g, 0.044 meq/g) and it is the current flow depends on the surface area conductivity as well as the conductivity of the pore fluid. This can be seen more clearly in Figure 6.9 for clean sands that have very high electrical resistance (R > 5000 Ohm) whose particles have very small surface area and *CEC* which means the effect of the surface area and *CEC* of sand particles can be neglected. Thus, it would be expected that the overall electrical conductivity in sands is only a function of its pore water conductivity.

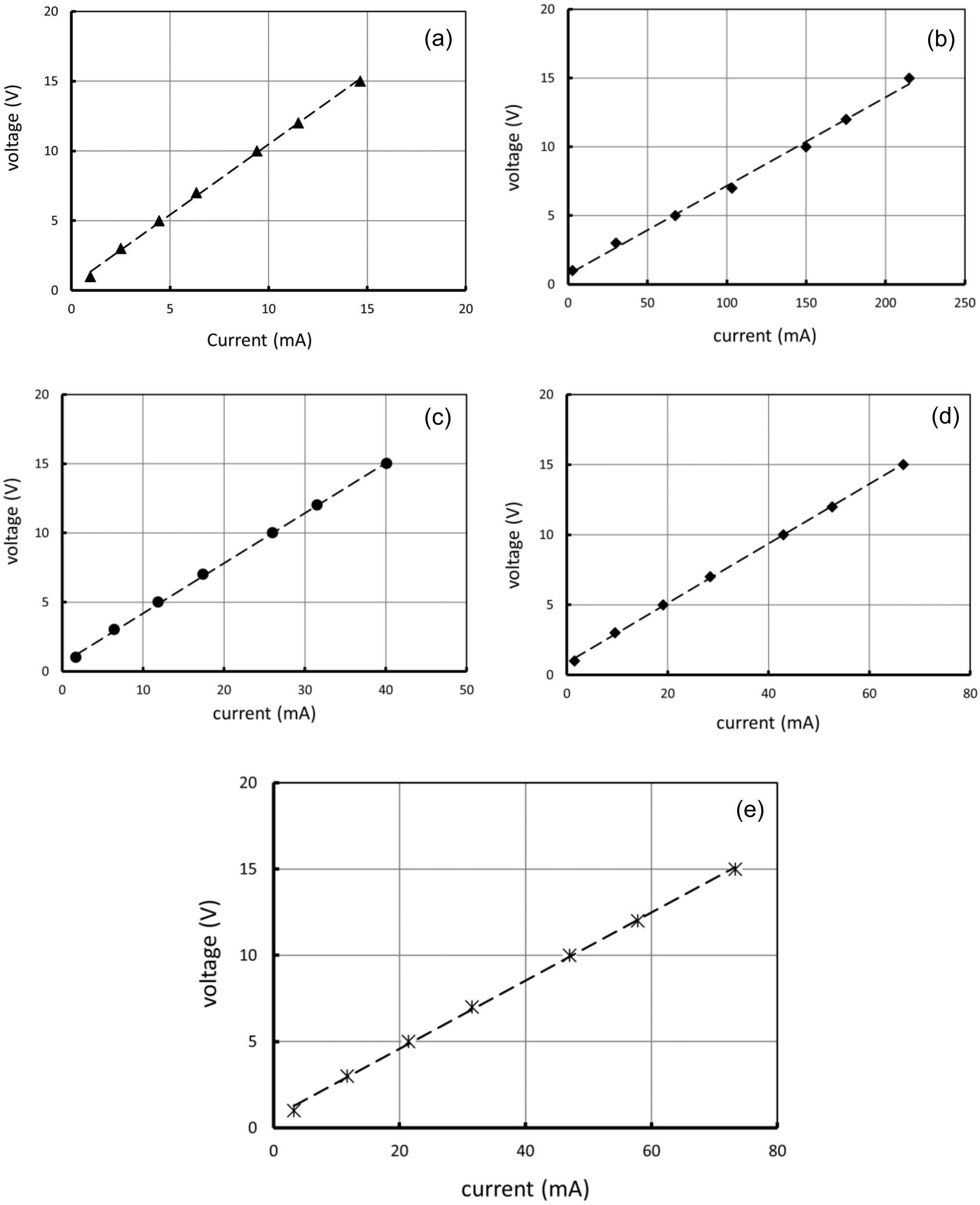


Figure 6.8: Typical voltage-current profile of clays; (a) kaolinite, (b) bentonite, (c) illite, (d) sepiolite, (e) attapulgite

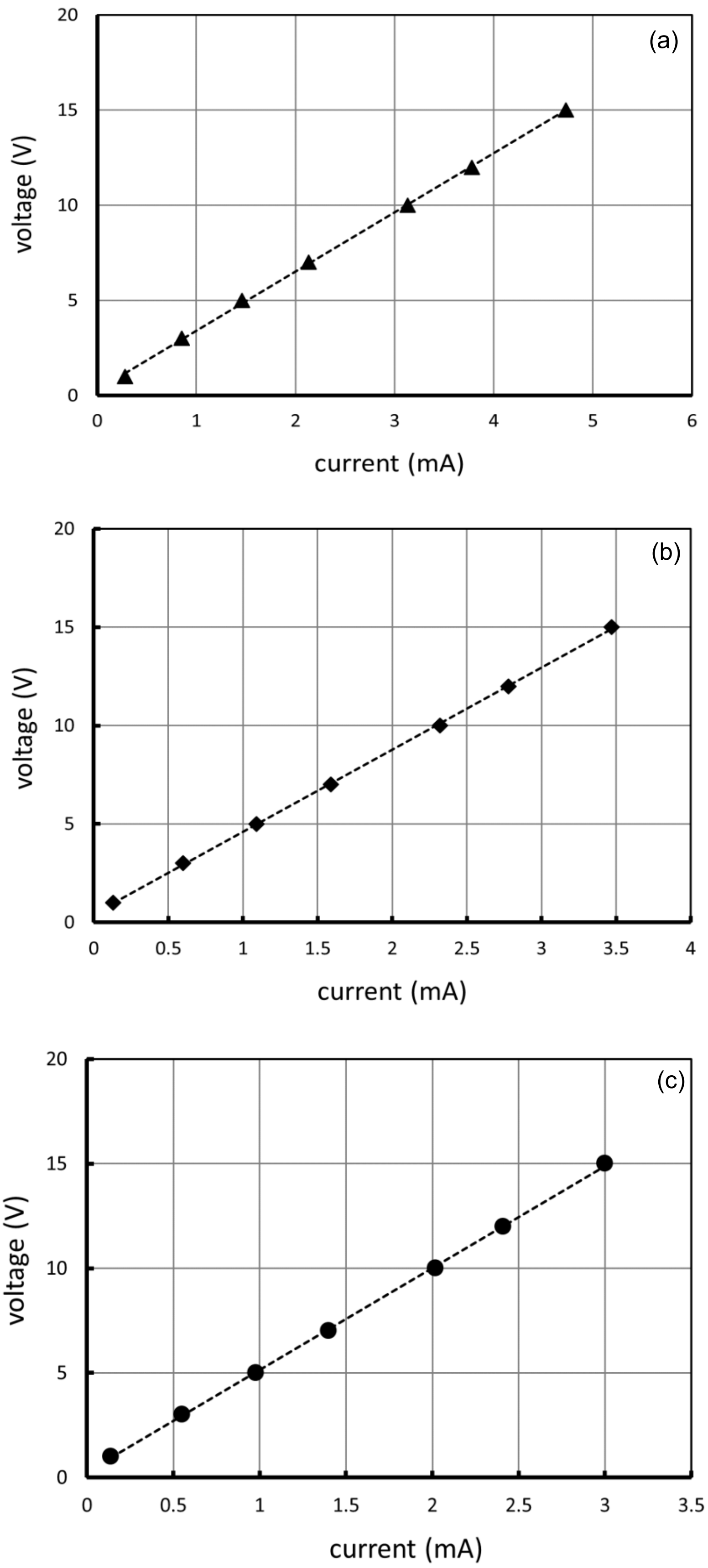


Figure 6.9: Typical voltage-current profile of sands; (a) fine sand, (b) medium sand, (c) mixed sand.

As described in chapter three, section 3.4.4.5, the electrical conductivity of all composite soil mixtures was determined using equ. 3.8 & 3.9 depending on the value of the resistance that was obtained from (*V-I*) relationship, e.g. in Figure 6.8 and Figure 6.9, the length of the sample being tested, and its cross-sectional area. A summary of the results of the electrical conductivity of all composite soil mixtures is presented below in Tables 6.2, 6.3, 6.4, 6.5, 6.6, and 6.7.

Table 6.2: The electrical conductivity results of composite fine sand-illite mixtures

Composite fine sand-illite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio n	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Electrical conductivity (S/m)
FSI100	100	0	0.512	0.512	-	1.30	43.21	0.0454
			0.401	0.401	-	1.60	28.87	0.0435
			0.317	0.317	-	1.82	23.00	0.0381
FSI80	80	20	0.470	0.526	0.894	1.41	37.43	0.0370
			0.380	0.434	0.876	1.65	26.48	0.0334
			0.290	0.338	0.858	1.89	17.58	0.0281
FSI60	60	40	0.440	0.567	0.776	1.48	33.55	0.0256
			0.380	0.505	0.752	1.64	24.48	0.0256
			0.270	0.381	0.708	1.93	15.88	0.0184
FSI40	40	60	0.380	0.605	0.628	1.64	25.00	0.0185
			0.330	0.552	0.598	1.77	20.00	0.0157
			0.240	0.441	0.544	2.01	13.00	0.0130
FSI20	20	80	0.341	0.721	0.472	1.73	20.80	0.0108
			0.297	0.679	0.438	1.85	16.99	0.0101
			0.263	0.641	0.410	1.94	14.40	0.0072
FS	0	100	0.408	-	0.408	1.56	21.97	0.0052
			0.390	-	0.390	1.64	18.20	0.0044
			0.370	-	0.370	1.68	16.28	0.0035

Table 6.3: The electrical conductivity results of composite mixed sand-kaolinite mixtures

Composite mixed sand-kaolinite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio n	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Electrical conductivity (S/m)
SK100	100	0	0.536	0.536	-	1.21	45.96	0.0196
			0.507	0.507	-	1.28	37.60	0.0180
			0.492	0.492	-	1.32	36.12	0.0174
			0.426	0.426	-	1.49	26.81	0.0155
SK80	80	20	0.539	0.594	0.908	1.20	46.94	0.0180
			0.482	0.537	0.896	1.35	36.25	0.0160
			0.447	0.503	0.889	1.44	31.83	0.0152
			0.378	0.432	0.876	1.62	24.34	0.0132
SK60	60	40	0.535	0.657	0.814	1.22	48.32	0.0175
			0.467	0.594	0.787	1.40	37.79	0.0141
			0.389	0.515	0.756	1.60	28.13	0.0124
SK40	40	60	0.460	0.681	0.676	1.42	35.81	0.0120
			0.399	0.624	0.639	1.58	28.83	0.0103
			0.360	0.584	0.616	1.60	25.15	0.0092
			0.331	0.553	0.598	1.76	21.68	0.0089
SK20	20	80	0.373	0.748	0.498	1.66	25.80	0.0073
			0.330	0.711	0.464	1.70	23.00	0.0060
			0.301	0.683	0.441	1.84	18.97	0.0053
			0.274	0.653	0.419	1.92	15.00	0.0043
S	0	100	0.333	-	0.333	1.77	18.20	0.0032
			0.323	-	0.323	1.79	16.28	0.0030
			0.302	-	0.302	1.85	12.86	0.0025

Table 6.4: The electrical conductivity results of composite mixed sand-bentonite mixtures

Composite mixed sand-bentonite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio n	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Electrical conductivity (S/m)
SB100	100	0	0.710	0.710	-	0.74	104.18	0.2200
			0.655	0.655	-	0.88	79.68	0.2370
			0.630	0.630	-	0.94	73.00	0.2410
			0.591	0.591	-	1.04	62.84	0.2460
			0.542	0.542	-	1.17	59.19	0.2490
SB80	80	20	0.588	0.836	0.918	1.06	65.00	0.2039
			0.543	0.809	0.909	1.15	55.00	0.2077
			0.487	0.772	0.897	1.30	45.00	0.2100
			0.450	0.745	0.890	1.41	39.76	0.2110
SB60	60	40	0.543	0.664	0.817	1.18	51.85	0.1640
			0.487	0.613	0.795	1.33	40.58	0.1633
			0.440	0.567	0.776	1.40	35.00	0.1640
			0.410	0.537	0.764	1.53	32.00	0.1701
SB40	40	60	0.519	0.730	0.711	1.26	45.27	0.1193
			0.459	0.680	0.676	1.41	36.79	0.1175
			0.393	0.618	0.636	1.58	29.18	0.1100
			0.370	0.595	0.622	1.64	27.01	0.1100
SB20	20	80	0.501	0.834	0.601	1.31	40.17	0.0757
			0.456	0.807	0.565	1.43	32.00	0.0732
			0.399	0.768	0.519	1.50	26.69	0.0669
			0.350	0.729	0.480	1.70	23.60	0.0594
S	0	100	0.333	-	0.333	1.77	18.20	0.0032
			0.323	-	0.323	1.79	16.28	0.0030
			0.302	-	0.302	1.85	12.86	0.0025

Table 6.5: The electrical conductivity results of composite fine sand-kaolinite mixtures

Composite fine sand-kaolinite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio n	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Electrical conductivity (S/m)
FSK100	100	0	0.536	0.536	-	1.21	45.96	0.0196
			0.507	0.507	-	1.28	37.60	0.0180
			0.492	0.492	-	1.32	36.12	0.0174
			0.426	0.426	-	1.49	26.81	0.0155
FSK80	80	20	0.535	0.590	0.907	1.21	49.22	0.0170
			0.500	0.556	0.900	1.26	43.64	0.0159
			0.450	0.505	0.890	1.43	36.43	0.0142
			0.383	0.437	0.877	1.60	28.26	0.0130
FSK60	60	40	0.563	0.683	0.825	1.14	52.83	0.0170
			0.467	0.594	0.787	1.39	37.86	0.0132
			0.381	0.506	0.752	1.62	28.05	0.0100
FSK40	40	60	0.506	0.719	0.703	1.30	41.85	0.0139
			0.430	0.653	0.658	1.45	31.95	0.0098
			0.388	0.613	0.633	1.60	27.23	0.0085
FSK20	20	80	0.408	0.775	0.526	1.56	26.85	0.0076
			0.325	0.707	0.460	1.78	19.30	0.0049
			0.307	0.688	0.445	1.82	17.91	0.0042
			0.290	0.671	0.432	1.84	16.76	0.0037
FS	0	100	0.408	-	0.408	1.56	21.97	0.0052
			0.390	-	0.390	1.64	18.20	0.0044
			0.370	-	0.370	1.68	16.28	0.0035

Table 6.6: The electrical conductivity results of composite medium sand-sepiolite mixtures

Composite medium sand-sepiolite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio n	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Electrical conductivity (S/m)
MSSP100	100	0	0.695	0.695	-	0.70	106.15	0.0829
			0.637	0.637	-	0.83	82.77	0.0886
			0.600	0.600	-	0.90	71.49	0.091
			0.580	0.580	-	0.98	65.00	0.0915
MSSP80	80	20	0.653	0.701	0.931	0.83	84.26	0.0747
			0.598	0.651	0.920	0.96	68.55	0.0775
			0.543	0.598	0.909	1.09	56.12	0.0782
			0.525	0.580	0.905	1.20	52.77	0.0780
MSSP60	60	40	0.630	0.739	0.852	0.90	67.55	0.0645
			0.560	0.680	0.824	1.10	55.12	0.0646
			0.490	0.616	0.796	1.25	50.77	0.0638
			0.470	0.596	0.788	1.40	45.00	0.0630
MSSP40	40	60	0.590	0.783	0.754	1.04	60.00	0.0474
			0.519	0.729	0.711	1.22	45.96	0.0462
			0.470	0.689	0.682	1.36	38.88	0.0453
			0.428	0.651	0.657	1.45	34.40	0.0440
MSSP20	20	80	0.486	0.826	0.589	1.34	37.50	0.0338
			0.412	0.778	0.530	1.53	29.08	0.0297
			0.370	0.746	0.496	1.59	24.53	0.0266
			0.356	0.734	0.485	1.68	23.03	0.0248
MS	0	100	0.364	-	0.364	1.68	18.91	0.0033
			0.353	-	0.353	1.72	16.28	0.0029
			0.340	-	0.340	1.76	12.86	0.0024

Table 6.7: The electrical conductivity results of composite medium sand-attapulgite mixtures

Composite medium sand-attapulgite mixtures	Clay content (%)	Sand content (%)	Porosity based on global void ratio n	Porosity based on matrix void ratio n_m	Porosity based on intergranular void ratio n_i	Dry density (Mg/m^3)	Water content (%)	Electrical conductivity (S/m)
MSAG100	100	0	0.807	0.807	-	0.40	210.68	0.0640
			0.763	0.763	-	0.49	167.63	0.0670
			0.696	0.696	-	0.63	122.07	0.0690
			0.640	0.640	-	0.70	102.55	0.0700
MSAG80	80	20	0.786	0.821	0.957	0.47	175.51	0.0573
			0.712	0.756	0.942	0.63	122.71	0.0592
			0.640	0.690	0.928	0.86	88.87	0.0603
			0.586	0.639	0.917	0.91	74.71	0.0604
MSAG60	60	40	0.761	0.841	0.904	0.56	143.06	0.0472
			0.689	0.787	0.876	0.72	102.34	0.0469
			0.600	0.714	0.840	1.00	68.01	0.0460
			0.489	0.615	0.796	1.19	50.21	0.0450
MSAG40	40	60	0.685	0.845	0.811	0.77	95.34	0.0337
			0.543	0.748	0.726	1.12	55.56	0.0322
			0.500	0.715	0.700	1.22	46.71	0.0306
			0.480	0.698	0.688	1.32	37.00	0.0283
MSAG20	20	80	0.486	0.826	0.589	1.30	41.00	0.0232
			0.412	0.778	0.530	1.45	32.00	0.0195
			0.370	0.746	0.496	1.56	28.00	0.0162
			0.356	0.734	0.485	1.60	26.00	0.0148
MS	0	100	0.364	-	0.364	1.68	18.91	0.0033
			0.353	-	0.353	1.72	16.28	0.0029
			0.340	-	0.340	1.76	12.86	0.0024

6.3.1 Electrical conductivity-porosity relationships

The variation of the overall electrical conductivity (σ_T) with soil porosity (n) is shown in Figure 6.10 for all the composite soils prepared with tap water of low conductivity (σ_w = 0.0343 S/m). It can be seen that there is either a direct or inverse relationship between (σ_T) and (n) depending on water conductivity (σ_w) and particle surface conductivity (σ_s) that originally emerges from particle-contacts and/ or from the diffusion double layer.

If the conductivity of the particle surfaces (σ_s) is less than the conductivity of water (σ_w), the overall conductivity (σ_T) increases as the porosity increases, which is consistent with an increase in water content. The preferred path for the electric current to flow will be through the most conductive ionic-water in the soil pores, and increasing porosity (pores) can eventually result in increasing the magnitude of the soil's electrical conductivity. This occurs mostly in composite soils of low cation exchange capacity which depends on clay type and content in the soils.

However, in composite soils with a higher *CEC* (typically composite soils ≥ 80% clay content, except the mixtures of kaolinite and illite), an inverse relationship is exist between (σ_T) and (n). In this case, the negatively charged surfaces on the clay particles would be the more preferred path for the current migration through the soil, thus increasing the porosity can cause the charged solid particles per volume to decrease reducing the magnitude of the soil's electrical conductivity (σ_T). Figure 6.10 also indicates that at a given porosity, the overall electrical conductivity increases when the clay content increases attributing that to an increase in the surface conductivity (σ_s) with increasing clay content.

Note that the previous discussion was for composite soils prepared with relatively low water salinity (low water conductivity). This may not be applicable if there is a high water conductivity. In general, the interplay between porosity, clay and bulk water conductance affect the overall behaviour of electrical conductivity in composite soils.

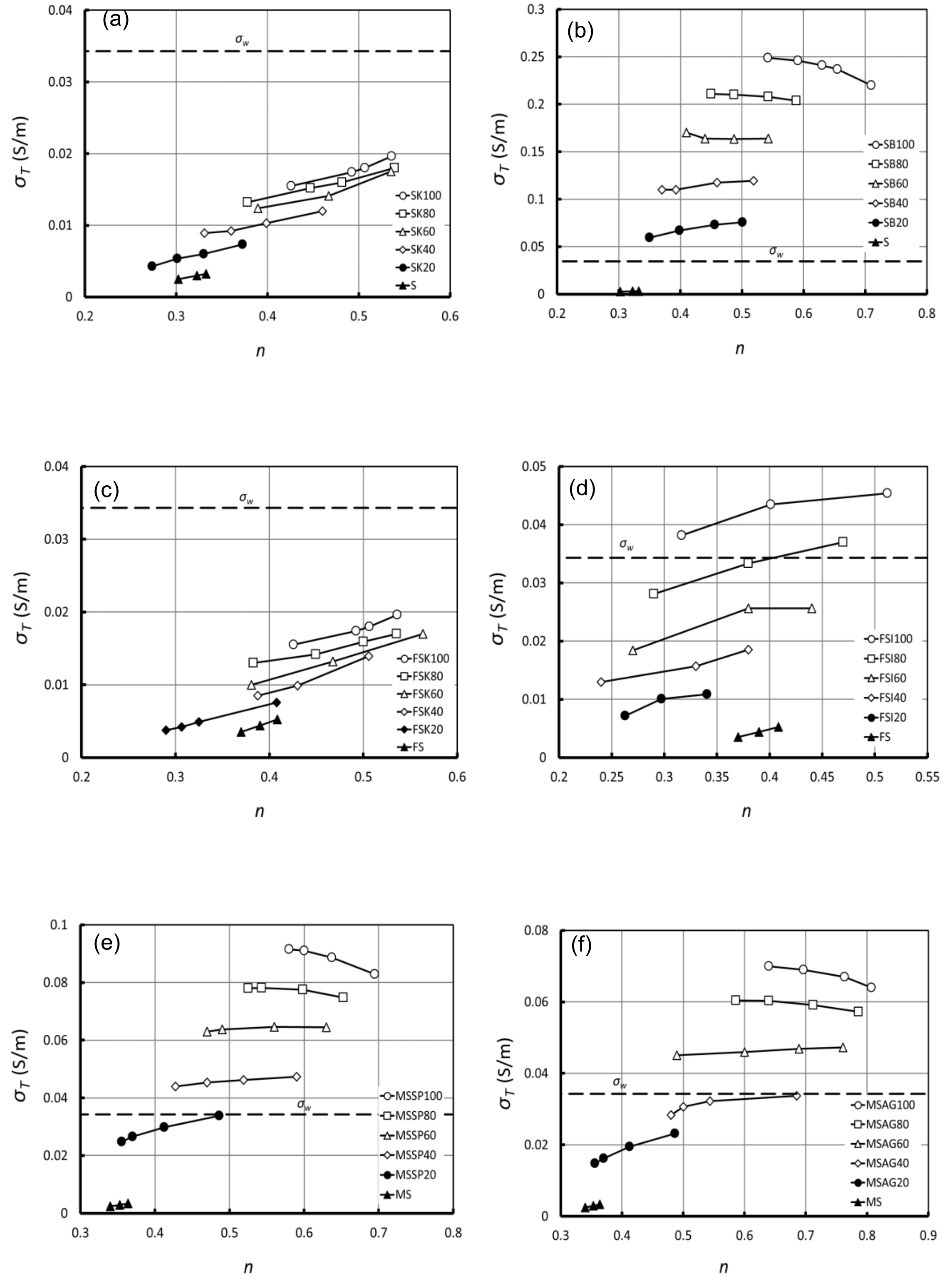


Figure 6.10: The variation of the overall soil conductivity with the porosity of: (a) mixed sand-kaolinite, (b) mixed sand-bentonite, (c) fine sand-kaolinite, (d) fine sand-illite, (e) medium sand-sepiolite, (f) medium sand-attapulgite mixtures.

6.3.2 Electrical conductivity-water content relationships

The relationship between the overall conductivity and water content is plotted in Figure 6.11 for all composite soils. Similar to the porosity, the relationship is either direct or inverse depending on the magnitude of pore water and clay particle conductivity.

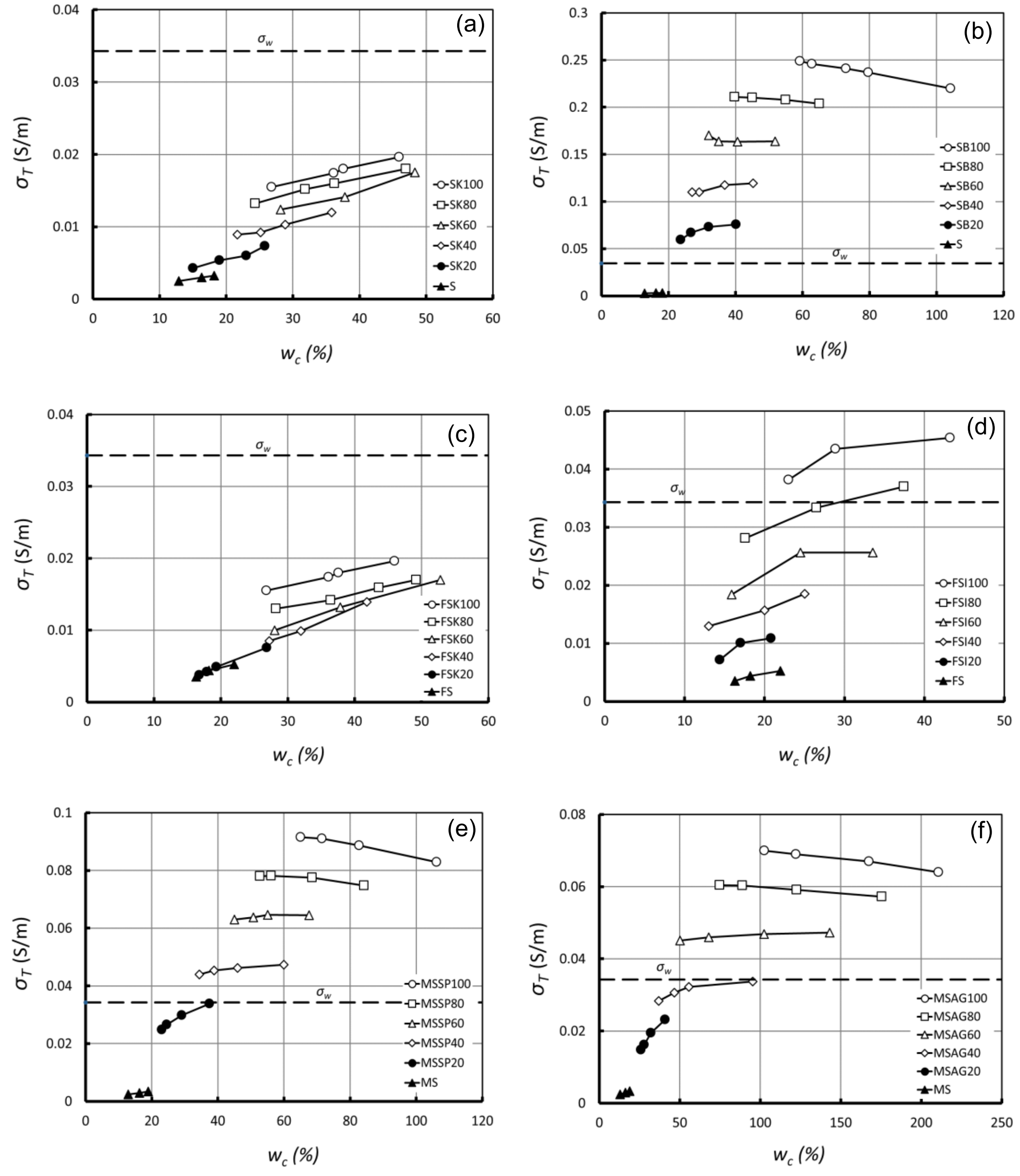


Figure 6.11: The variation of the overall soil conductivity with the water content of: (a) mixed sand-kaolinite, (b) mix sand-bentonite, (c) fine sand-kaolinite, (d) fine sand-illite, (e) medium sand-sepiolite, (f) medium sand-attapulgite mixtures.

6.3.3 Influence of water conductivity on the overall soil conductivity

In the previous electrical tests, all composite soil mixtures were prepared with tap water of relatively low conductivity value. To find the influence the pore water conductivity has on the overall soil conductivity, additional tests on pure clays blended with distilled water of very low (0.00047 S/m) conductivity were carried out and the overall electrical conductivity of the clay samples was measured.

Figure 6.12 shows the relationship between the overall electrical conductivity (σ_T) and porosity (*n*) of kaolinite, bentonite, illite, sepiolite and attapulgite clays using tap water and distilled water. It can be noted that σ_T of the clays prepared with the tap water are generally higher than that for the clays mixed with distilled water which could be due to the higher electrical conductivity of the tap water. The trend of the relationship in two cases is clearly similar for bentonite, sepiolite and attapulgite clays in which σ_T decreases with increasing porosity. However, for kaolinite and illite, increasing the porosity will increase the σ_T when prepared with tap water and its reverse when prepared with distilled water.

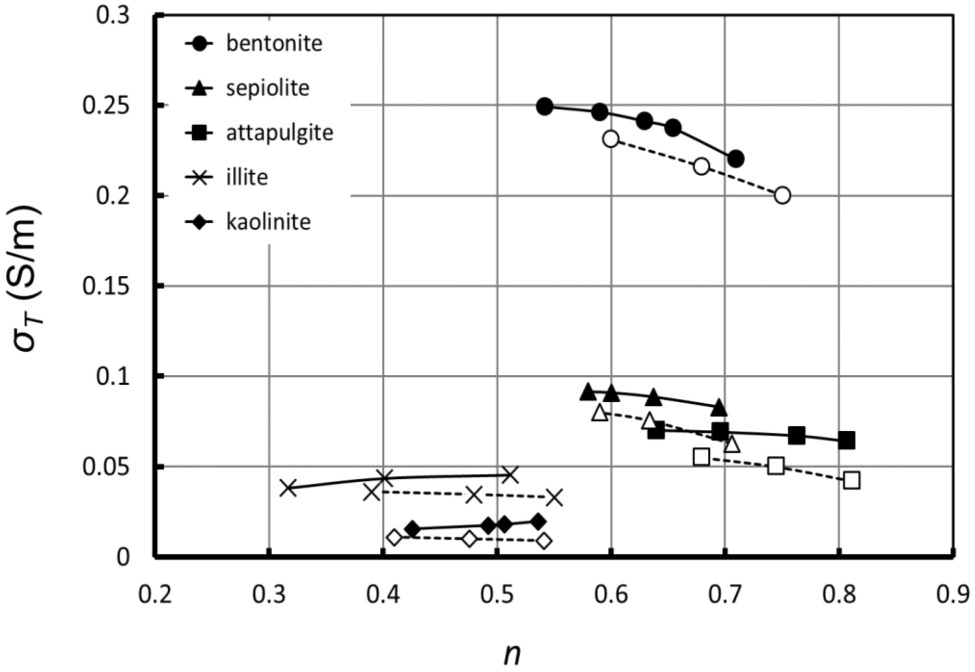


Figure 6.12: The elctrical conductivity-porosity of pure clays with tap water (solid markers) and with distilled water (open markers)

The probable explanation of the behaviour in Figure 6.12 can be due to the interplay between the conductivity of water and clay surfaces. In bentonite, sepiolite and attapulgite, in both tap and distilled water, the conductivity of particle surfaces dominates the electricity transfer and increasing the porosity can only cause a reduction in the conductive solid particles in the unit volume, which eventually decreases the overall conductivity. In kaolinite and illite, if prepared with tap water, the current is mostly controlled by the water conductivity and increasing porosity increases the flow path leading to an increase in the overall electrical conductivity. However, for kaolinite and illite prepared with distilled water, it's the surface conductivity that governs the current flow through these clays and increasing the porosity results in decreasing the overall conductivity.

In composite sand-clay soils, the overall electrical conductivity (σ_T) can be modelled as a parallel function of two main components; bulk pore fluid conductance (E_w) and clay minerals conductance (E_s) within the soil:

$$\sigma_T = E_w + E_s \tag{6.4}$$

Where E_w and E_s are dependent on the conductivity of fluid (σ_w) and clay particle surfaces (σ_s), respectively, and their volumetric fractions.

The electrical conductivity of distilled water is very low compared to that of clay particle surfaces meaning that the bulk electrical conductance of distilled water in the mixtures, $E_{w,\ distilled}$, will be too low with respect to that of clay mineral conductance, E_s. For example, in kaolinite, whose particles have the least electrical conductivity amongst all the clays because of its low CEC and surface area, at a certain porosity, the bulk distilled pore water conductance is about ($E_{w,\ distilled}$ = 0.000107 S/m) whereas the kaolinite mineral conductance is around (E_s = 0.011 S/m). In other clays (e.g. bentonite), the difference is much larger ($E_{w,\ distilled}$ = 0.00023 S/m vs E_s = 0.25 S/m). If the bulk conductance of the distilled water is to be neglected, then the overall electrical conductivity of clays with distilled water ($\sigma_{T,distilled}$) should be equal only to the conductance of clay minerals (E_s):

$$\sigma_{T,distilled} = E_s \tag{6.5}$$

In this case, for a particular clay type and porosity, the difference between the overall conductivity of soil with tap water ($\sigma_{T,\ tap}$) and that with distilled water ($\sigma_{T,\ distilled}$) equals the bulk water conductance (E_w) in the soil as:-

$$E_{w,tap} = \sigma_{T,tap} - E_s = \sigma_{T,tap} - \sigma_{T,distilled} \qquad (6.6)$$

The work of Archie (1942) assumes that the water conductance, E_w, in nonconductive sandy soils represents the water conductivity and their respective volume fraction (porosity) as:

$$E_w = n^m . \sigma_w \qquad (6.7)$$

The value of m was assumed to be 2, the average value suggested by Archie and by Sen et al. (1988). To check whether the above concept (equ. 6.7) can be applied to conductive clayey soils, a comparison between the water conductance found from the difference in overall conductivities (E_w in equ. 6.6) and water conductance found from Archie's model (E_w in equ. 6.7) is made in Figure 6.13. It can be seen that there is a reasonable agreement between them suggesting that it is possible to extend the concept of Archie's law for water conductance for clayey soils using an average of *m* = 2.

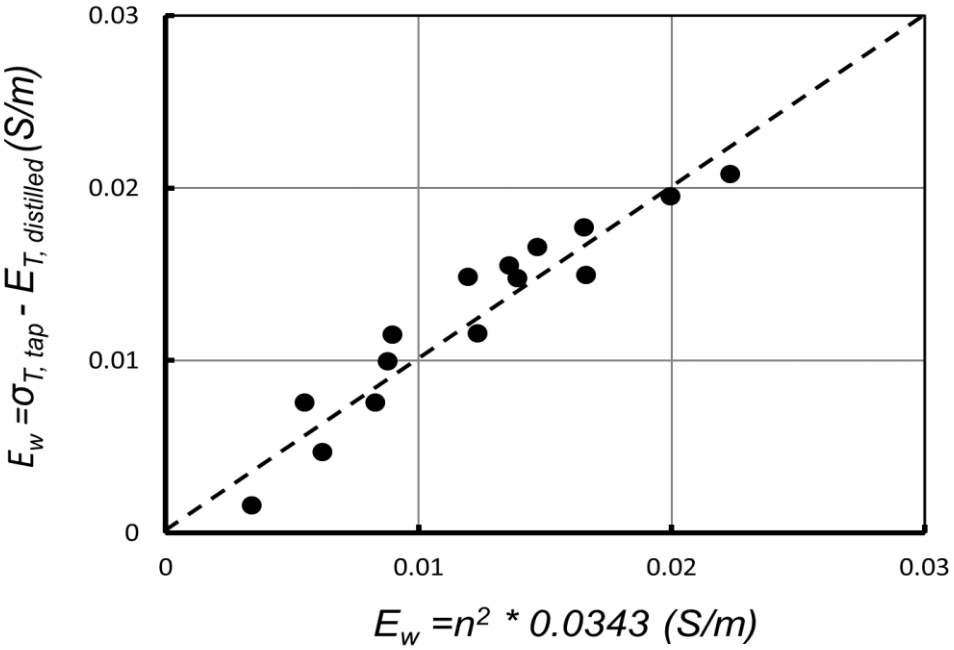


Figure 6.13: A comparison between the water conductance determined from $E_w = \sigma_{T,\ tap} - \sigma_{T,\ distilled}$, and that determined following Archie's model of pure clays

6.3.4 Influence of clay content and conductivity on the overall soil conductivity

A review of Figure 6.10 and Figure 6.11 shows that the overall soil electrical conductivity is a function of pore water conductivity, and clay content and type in the soils. An increase in clay content is expected to cause an increase in the electrical conductivity because of the effect of the negative charges available on the surface of the clay particles as it provides a path other than the pore fluid for current to flow.

The effect of clay content on the overall electrical conductivity of composite soils prepared with tap water of low conductivity (0.0343 S/m) is presented in Figure 6.14. Each data point at a given clay content represents a different porosity. The comparison with clay content should be based on a common porosity among all mixtures' porosities so that the effect of the water fraction is the same for all samples. Thus, the solid line represents the best fit for the values of the electrical conductivity at porosity, n = 0.5, the most common porosity among all mixtures' porosities. The electrical conductivity at n = 0.5, shown with solid markers in Figure 6.14, was determined from the best-fit equation of (σ_T-n) relationship.

Initially, at a clay content of zero, the electrical conductivity of composite soil mixtures is governed by the geometrical arrangement of the pores between the sand particles and the electrical conductivity of the water available in the pores because current transfers only though the pore water in the soil mixture. Once the clay content increases, the clay particles fill the pores between the coarser sand particles and the current will flow though the pore water and along the surfaces of the clay particles. This leads to an increase in the electrical conductivity of the soil mixtures. When the clay content increases further and further, the sand particles are distributed randomly in the mixture with no effective contacts and the electrical conductivity of clays controls the overall soil mixture conductivity. The effect of the amount of clay on the overall soil electrical conductivity appears clearly when the electrical conductivity of the soil water is low, in other word, when it's lower than the electrical conductivity of the clay particle surfaces.

The rate of increase in the electrical conductivity and the behaviour in Figure 6.14 may have a different trend if the composite soil mixtures are prepared with water of high electrical conductivity.

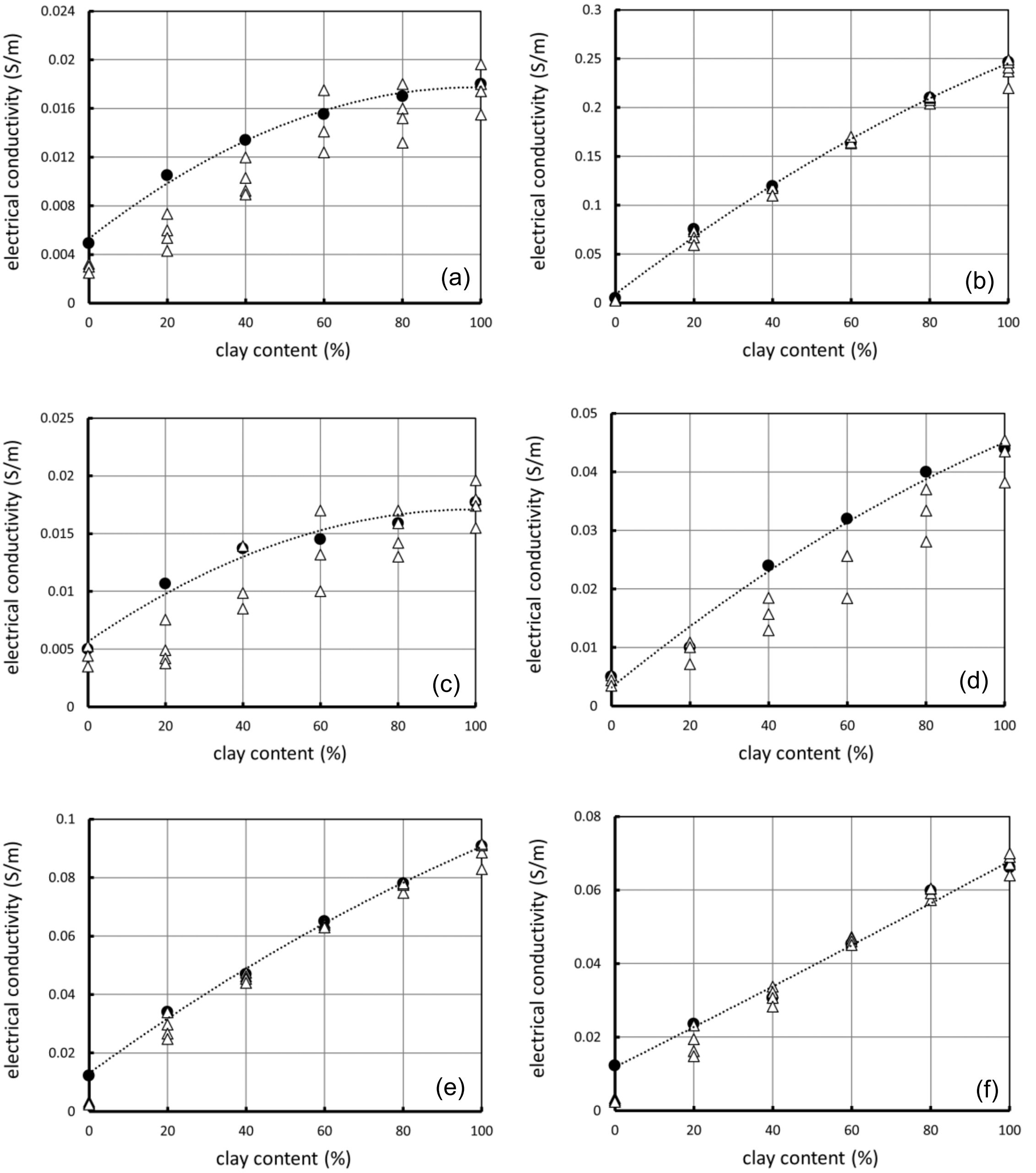


Figure 6.14: Effect of clay content on the electrical conductivity of composite soils; (a) mixed sand-kaolinite, (b) mixed sand-bentonite, (c) fine sand-kaolinite, (d) fine sand-illite, (e) medium sand-sepiolite, (f) medium sand-attapulgite mixtures

To assess the implementation of the concept of matrix and intergranular void ratios, that has been described in chapter two, section 2.3, for the electrical conductivity, the porosity based on the matrix void ratio (n_m) and intergranular void ratio (n_i) was calculated and correlated with the overall electrical conductivity in composite soils in Figure 6.15, and Figure 6.16, respectively.

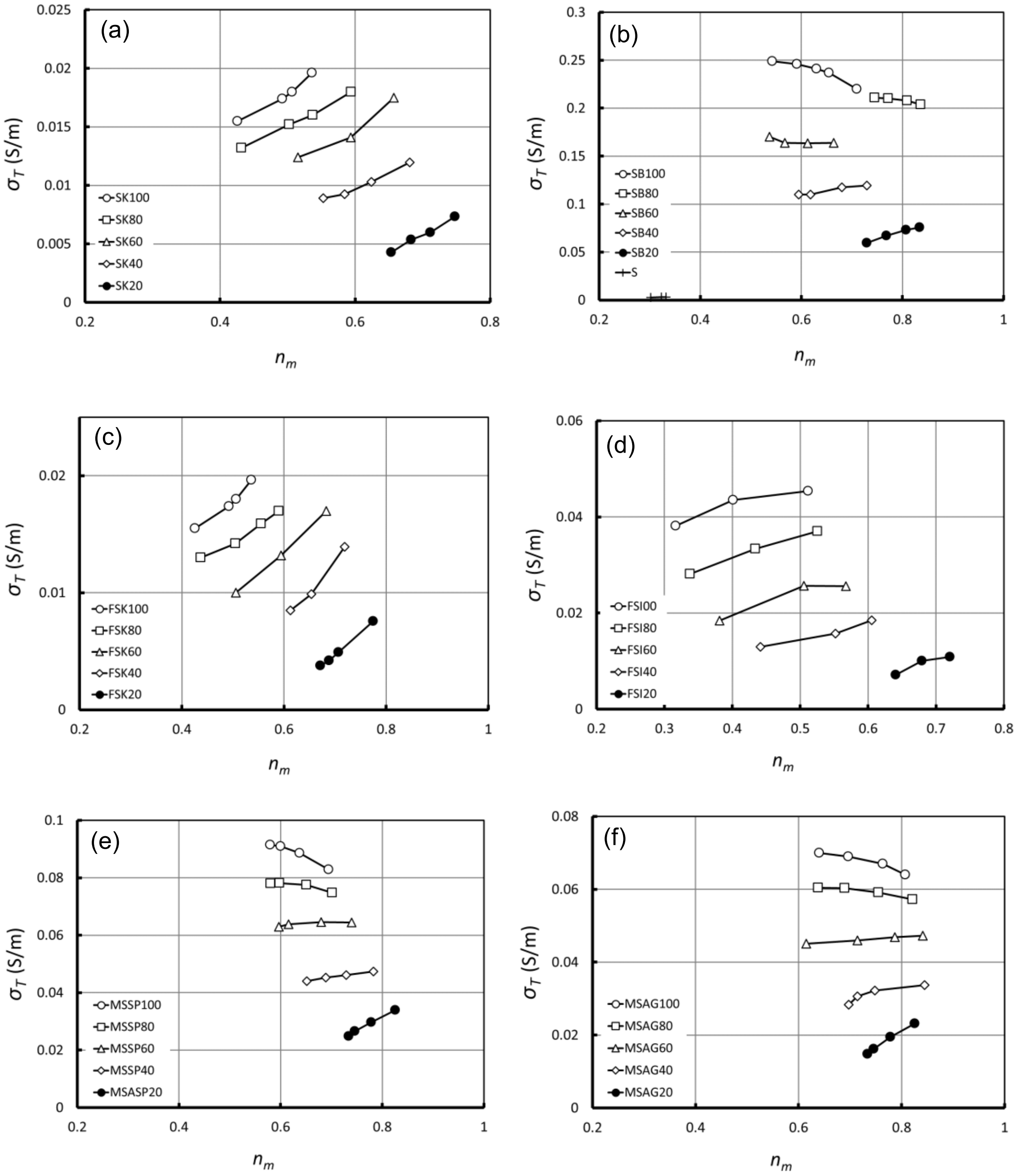


Figure 6.15: The relationship between the overall conductivity (σ_T) and porosity (n_m) based on the matrix void ratio in (a) mixed sand-kaolinite, (b) mixed sand-bentonite, (c) fine sand-kaolinite, (d) fine sand-illite, (e) medium sand-sepiolite, (f) medium sand-attapulgite mixtures

The figures show that the divergence between conductivity curves is higher than that with (n) in Figure 6.10 suggesting no significant relationship between (σ_T) and (n_m) and with (n_i). This confirms that the relationship of the electrical conductivity is much more complicated as it depends on the clay type and content and as well as porosity.

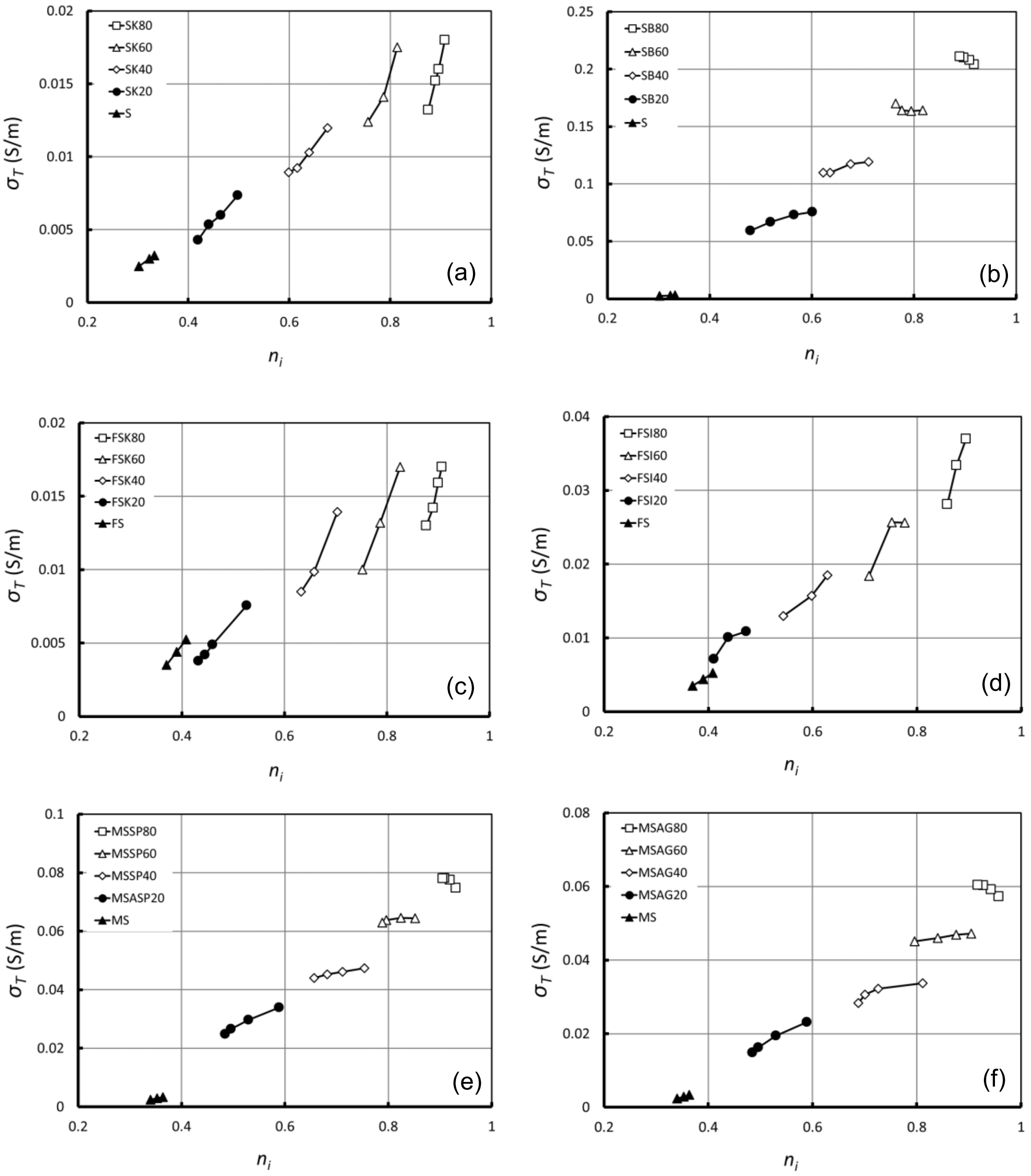


Figure 6.16: The relationship between the overall conductivity (σ_T) and porosity (n_i) based on the intergranular void ratio in (a) mixed sand-kaolinite, (b) mixed sand- bentonite, (c) fine sand-kaolinite, (d) fine sand-illite, (e) medium sand-sepiolite, (f) medium sand-attapulgite mixtures

The effect of clay conductance (E_s) can be computed from equ. (6.4) using the measured overall electrical conductivity (σ_T) and the bulk water conductance (E_w):-

$$E_s = \sigma_T - E_w = \sigma_T - n^m \sigma_w \qquad (6.8)$$

Figure 6.17 shows that for the majority of the composite soil data, particularly in composite soils of intermediate and high clay content, the clay conductance exceeds that of the tap water indicating the relevance contribution of their particle surface in electricity transfer. As the clay content decreases, the data approaches the equality line (1:1 line) and for clean sands, the clay conductance is negligible, thus, the data is located only on the horizontal axis confirming the fact that the electrical conductivity in sands is a function of the electrical conductivity of the pore water only

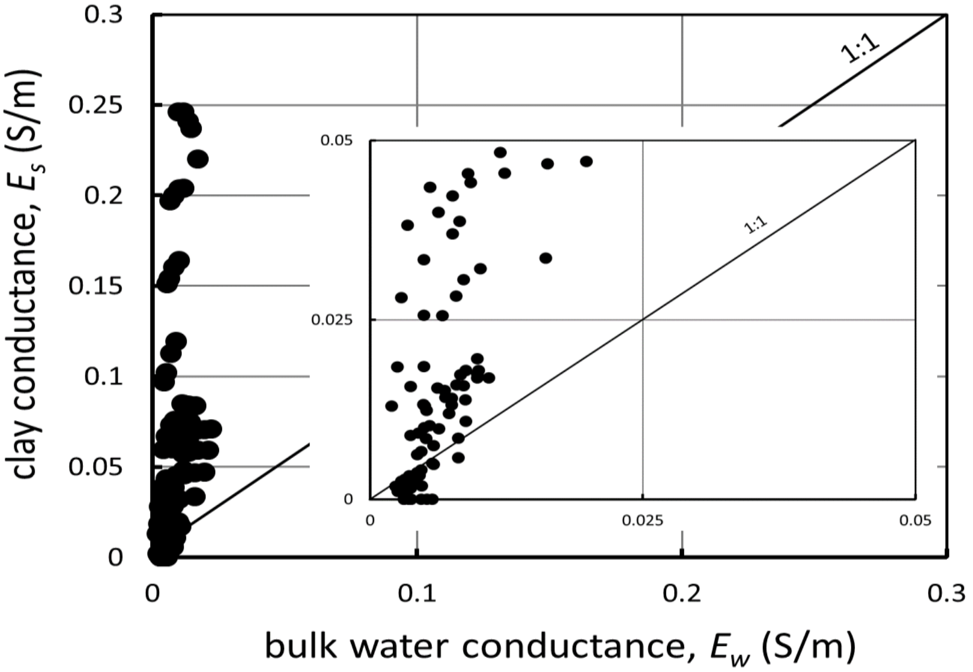


Figure 6.17: A comparison between the conductance of clay and that of the tap pore water

6.3.5 Use of electrical models with composite soils

Two common widely accepted semi-empirical models were used to estimate the values of the overall electrical conductivity of the composite soils used in this research. The electrical models include Waxman and Smits (1968) and Sen et al. (1988) models and the review of these models is presented in Chapter Two, Section 2.7.3.

They are based on the dual model and a triple model (see section 2.7.3 for more details). A comparison was made in Figure 6.18 using the data on composite soils prepared with tap water, and it was based on the following assumptions:

- The electrical conductivity of the clay surface particles (σ_s) in the Waxman and Smits formula was derived from the Equ 2.26, 27 and 28 using the porosity determined from the compression test and the cation exchange capacity determined from the methylene blue method.
- Archie's factor, *m*, was assumed to be 2. The tests on pure sands were interpreted using Archie's law to give an average value for m of 2, the same value proposed by Sen et al. (1988).

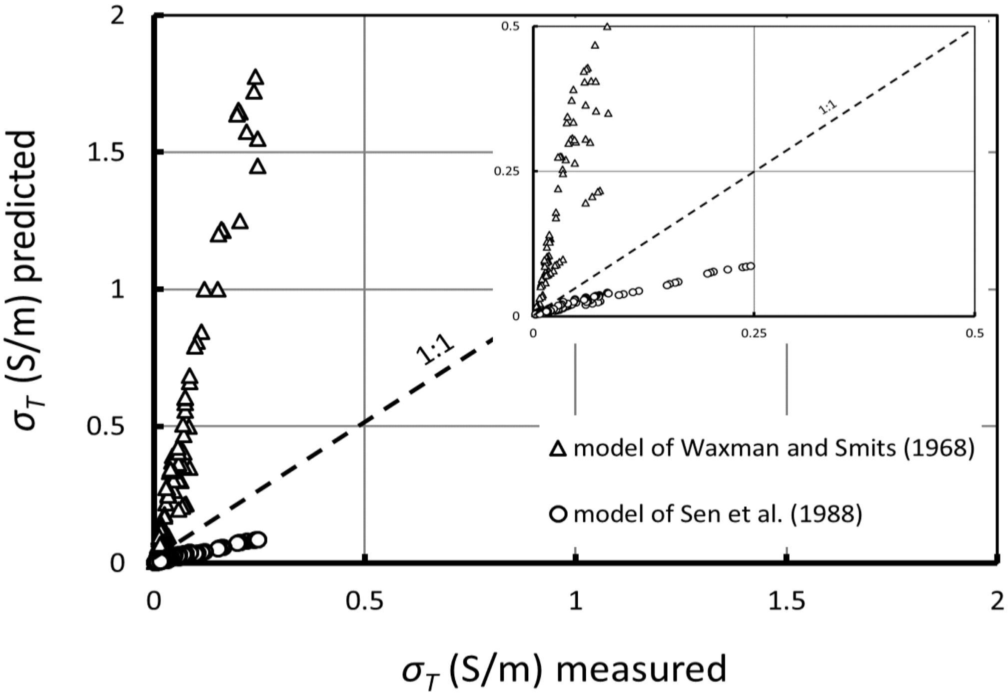


Figure 6.18: A comparison between the predicted electrical conductivity with the measured conductivity of composite soils

Figure 6.18 indicates that the overall electrical conductivity (σ_T) values predicted by Waxman and Smits, W-S, model are higher than the measured results, except for composite soils of low clay content and clean sands. This is normal as W-S model was based on the (σ_T - σ_w) relationship, shown in Figure 2.24, in which the water conductivity is always higher than clay surface conductivity. Thus, the values obtained from the W-S model for soils of high clay content, those of higher CEC, at condition of low water conductance ($E_s > E_w$) should be expected to be in a higher range. Similarly, the Sen et al. model shows a good fit with composite soils of low clay content (low *CEC*). However, the correlation then diverges for clay rich composite soils. This is due to the fact that the model of Sen et al. was developed from the same data used in the production of the W-S model, that is data of shaly sandstones with low clay content; i.e. the bulk water conductivity is always higher than the clay conductivity. Therefore, both models of W-S and Sen et al. are applicable only for composite soils of low clay content, more specifically for composite soils of low *CEC* and low specific surface area. For composite soils of high clay content (high *CEC*), where the electrical conductivity of the clay surface is greater than that of water, these models are not valid.

Figure 6.19 assesses how the values of Archie's cementation factor (*m*) varies with the amount and type of clay (expressed by the CEC). The Archie factor (*m*) was computed using Archie's equation (equ. 2.22 & 2.23) for all composite soils. It can be seen that Archie's factor, *m*, is not a constant since it varies with the cation exchange capacity of the soil which is derived from Figure 6.5 using clay content.

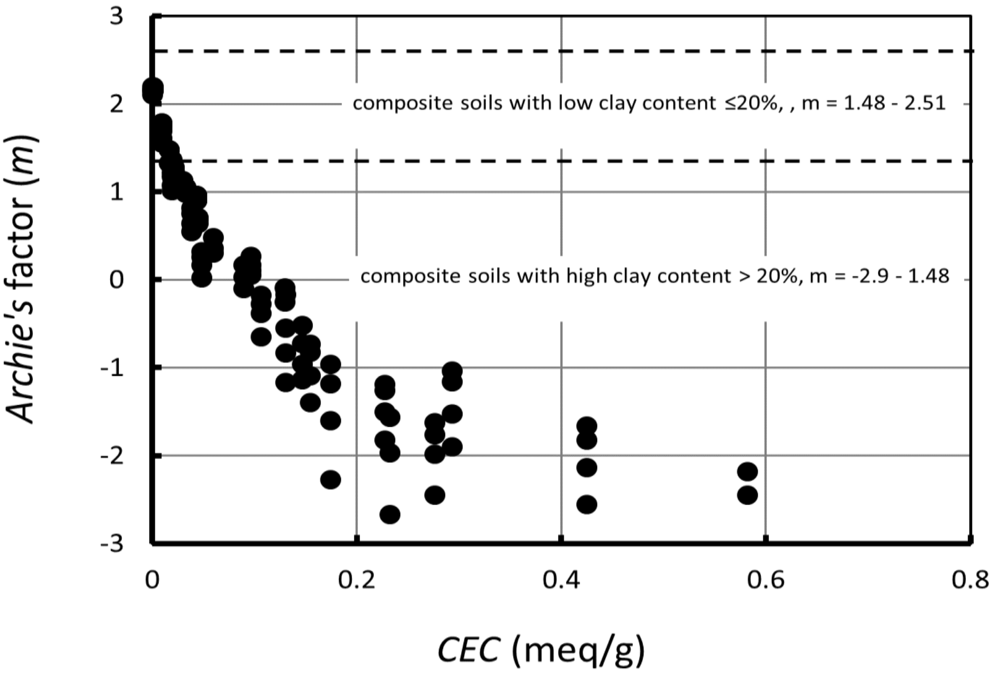


Figure 6.19: The variation of Archie's factor, *m*, with the cation exchange capacity (*CEC*) in composite soils

Values of (*m*) for composite soils range from (-2.9 – 2.51). For clean sands and composite soils of low clay amount, the factor m is positive (1.48 – 2.51). An increase in clay content implies, for soils with low pore fluid salinity, that the contribution the pore fluid conductivity makes to the overall conductivity reduces; hence the reduction in the m values. The negative value of m can be attributed to the contribution of clay conductance when the pore fluid has a low conductance. Archie's formula was developed originally for sandstones and the data used to validate the model included sandstones or shaly sand with a small amount of clay. Figure 6.19 emphases that the work of Archie (1942) is only valid for soils with very low clay conductance. As seen in section 6.3.3, however, Archie's principle can be extended for composite soils of high clay content at low water salinity by including the effect of clay mineral conductance that mainly depends on the type and amount of clay.

6.3.6 Semi-empirical models for the electrical conductivity of composite soils at low water conductivity

As stated earlier, the overall electrical conductivity of composite soils can be modelled as a parallel function of two main components; bulk pore fluid conductance (E_w) and clay minerals conductance (E_s) within the soil:

$$\sigma_T = E_w + E_s \qquad (6.9)$$

Where E_w and E_s are dependent on the conductivity of fluid (σ_w) and clay particle surfaces (σ_s), respectively, and their volumetric fractions.

In clean sands, the component (E_s) is neglected so the overall electrical conductivity is only a function of the electrical conductivity of water (σ_w) contained in the pore spaces and their volumetric fraction (porosity, n). This is consistent with the Archie's model that was developed for sandstones. In Figure 6.20, the best fit for the overall electrical conductivity for the sands used is in the form of:

$$\frac{\sigma_T}{\sigma_w} = 0.56 * n^{2.1} \qquad (6.10)$$

$$\sigma_T = 0.56 * \sigma_w * n^{2.1} = E_w \qquad (6.11)$$

In clay bearing composite soils, the clay conductance (E_s) can be found from equ. 6.9 as:

$$E_s = \sigma_T - E_w = \sigma_T - 0.56 * \sigma_w * n^{2.1} \qquad (6.12)$$

The determined clay conductance (E_s) was correlated with the cation exchange capacity (*CEC*) and the volumetric fraction of clay in the whole soil (x_{clay}) in Figure 6.21 to show there is a reasonable relationship with $R^2 = 0.981$:

$$E_s = 0.4272 * CEC * \left(x_{clay}\right)^{0.2} \tag{6.13}$$

x_{clay} is the volumetric fraction of clay in the whole sample which can be determined from the weight percentages of clay in the solid phase using:

$$x_{clay} = \frac{V_{clay}}{V_T} = \frac{C_m\,\gamma_d}{G_c\,\gamma_w} = \frac{C_m\,G_T(1-n)}{G_c}\,, \tag{6.14}$$

Where: C_m = percentage of clay by weight in the solid phase of the soil (% clay content), column 4 in Table 6.1.

γ_d = dry unit weight of soils (kN/m^3),

γ_w = unit weight of water (kN/m^3),

G_c = specific gravity of clay,

G_T = specific gravity of the whole soil mixture, column 5 in Table 6.1.

Therefore for all composite soils at low water conductivity, the final model can be written as

$$\sigma_T = 0.56 * \ \sigma_w * n^{2.1} + 0.4272 * CEC * \left(x_{clay}\right)^{0.2} \tag{6.15}$$

The overall electrical conductivity of all composite soils was determined using equ. 6.15 and compared to the measured values in Figure 6.22. It shows a reasonable agreement with *RMSE* of 0.0085 and $R^2 = 0.988$.

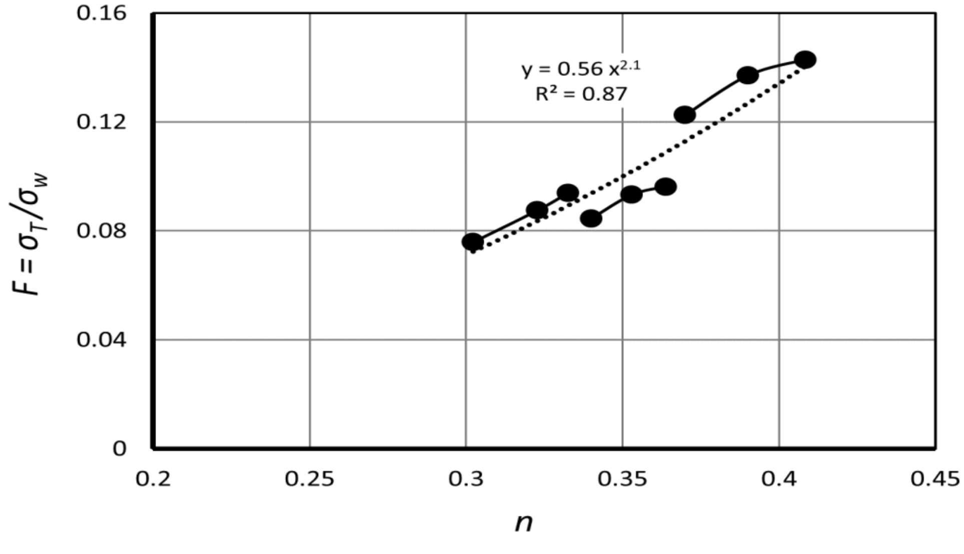


Figure 6.20: The relationship between formation factor ($F = \sigma_T/\sigma_w$) and porosity (n) for the sand used.

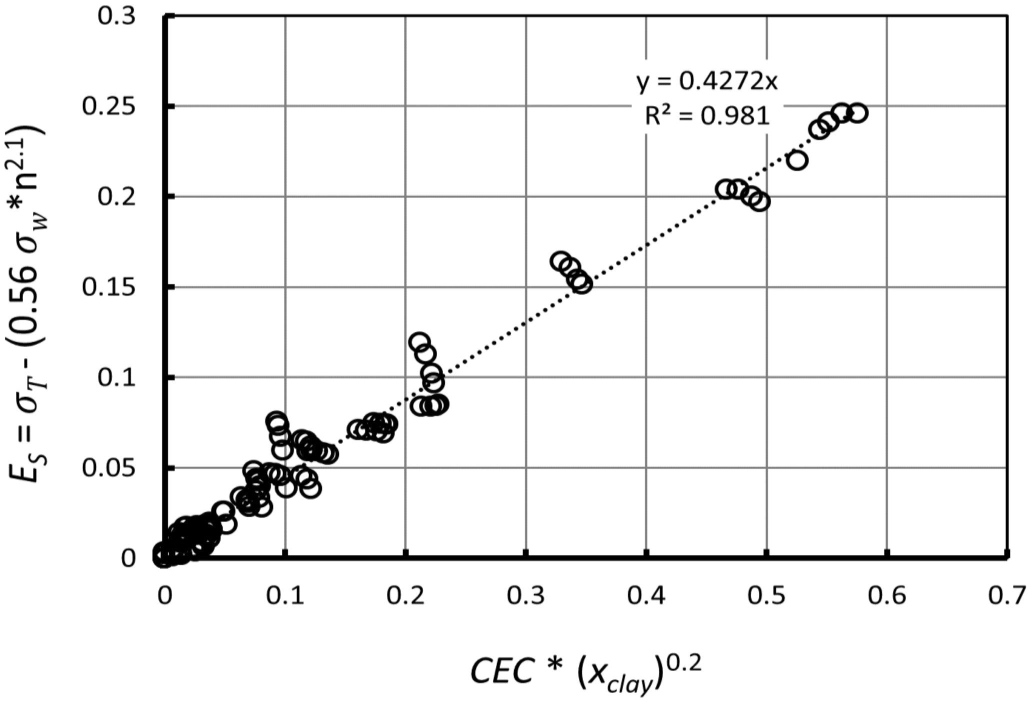


Figure 6.21: Clay conductance, E_s, as a function of cation exchange change (*CEC*) and volumetric fraction of clay, x_{caly}, in composite soils.

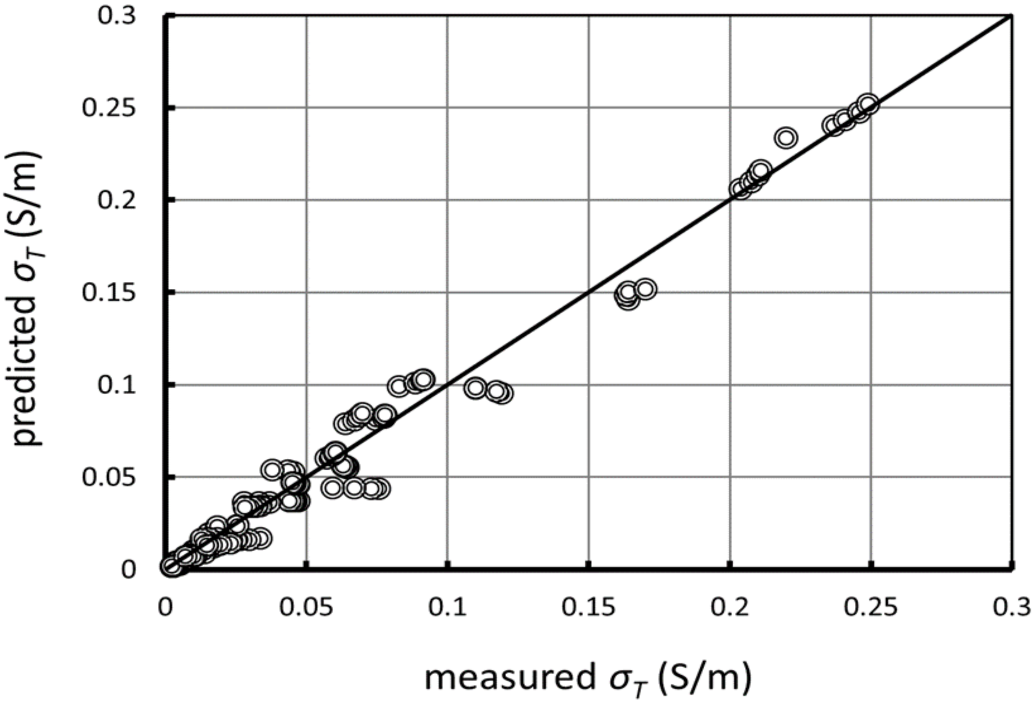


Figure 6.22: Predicted and measured values of electrical conductivity of composite soils using the new model (equ. 6.15)

An alternative approach for composite soils, and the basis of the Sen et al (1988) model, is to use three resistor elements to represent the pore fluid, the adsorbed water and the surface of the clay minerals. As seen in Figure 6.18, the Sen et al (1988) model provides a reasonable fit for composite soils with less than 20% clay content but is inappropriate for soils with a higher clay content. However, by selecting appropriate constants using data regression analysis, a good fit with *RMSE* of 0.0046 and R^2 = 0.994, as shown in Figure 6.23, to the test results can be obtained using:

$$\sigma_T = 0.7802n^2\sigma_w + 3.0702\left(\frac{1.93\ x\ 2\ x\ n^2 Q_v}{1+\frac{0.7}{\sigma_w}}\right) + 0.00439x\ Q_v \qquad (6.16)$$

Where n = soil porosity

Q_v = ionic concertation/volume (Meq/cm^3)

σ_w = pore water conductivity (S/m)

σ_T = overall electrical conductivity of composite soil (S/m)

For clean sands with no clay surface conductivity (Q_v = zero), the modified model (equ. 6.16) can reduce to Archie's model (the first term in equ. 6.16).

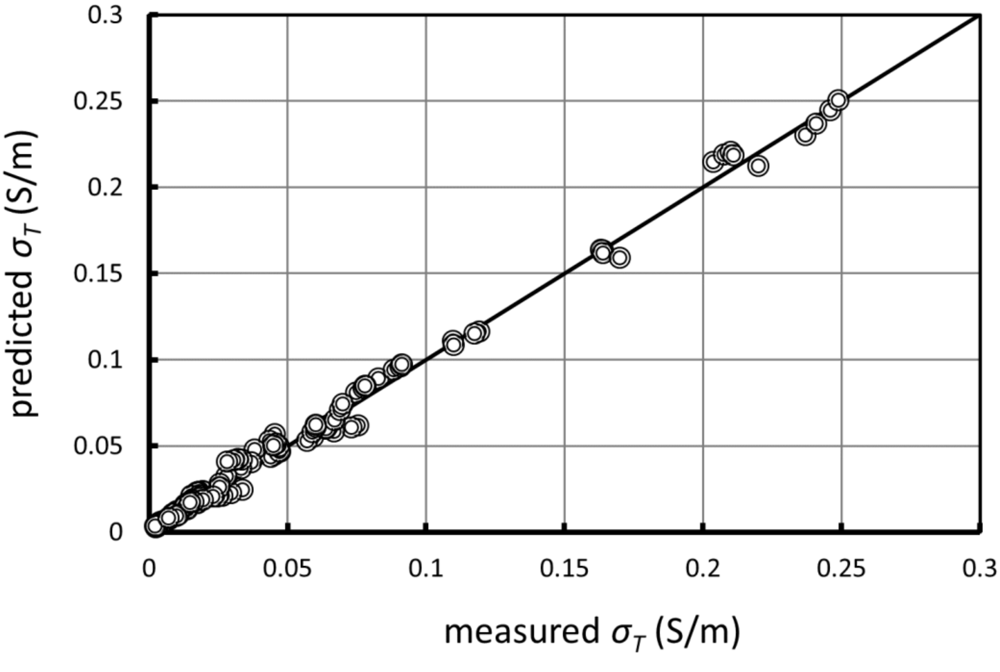


Figure 6.23: Predicted and measured values of electrical conductivity of composite soils using the modified Sen et al. (1988) model

6.4 Summary

This chapter summarises the test results for the electrical conductivity of a range of composite sand-clay soils prepared with tap and distilled water of very low electrical conductivity. It was shown that as the clay content increases the overall electrical conductivity of composite soils increases and there is either a direct or inverse correlation between the electrical conductivity and soil’s porosity or water content that depends mainly on the interplay between the clay and water conductance. Unlike hydraulic conductivity, there is no simple relationship between the electrical conductivity and porosity based on the matrix void ratio and that based on the intergranular void ratio indicating that the concept of matrix and intergranular void ratios could not be useful for interpreting the results of electrical conductivity in composite soils.

The interpretation of the electrical conductivity of composite sand-clay soils also demonstrated that the overall electrical conductivity in these soils can be modelled as a parallel function of two main components; bulk pore fluid conductance and clay minerals conductance within the soil that are dependent on the conductivity of fluid and clay particle surfaces, respectively, and their volumetric fractions. Test data on thirty seven samples of composite sand-clay soils prepared with tap water of low electrical conductivity showed that, for the majority of the data, the clay conductance exceeds that of bulk water indicating the importance of clay in the process of current transfer through soils. A soil mixture prepared with tap water of low electrical conductivity having higher cation exchange capacity (CEC) and specific surface area (As) (i.e. bentonite) will display a higher electrical conductivity than a soil with lower CEC and As (i.e. kaolinite, sand) at the same porosity.

The comparison between the measured values of the overall electrical conductivity of composite soils and those predicted by Waxman and Smits (1968) and Sen et al. (1988) models showed that they works well with clean sands and composite soils of low clay content (e.g. those having low CEC and As). However, for composite soils of high clay content prepared with tap water of low electrical conductivity (those that have high clay surface conductivity and low water conductivity), these models are not valid for estimating the overall electrical conductivity. Therefore, new empirical and modified models were developed for composite soils depending on clay and pore water conductivity and their amount in the whole soil.

Chapter 7
Conclusions and Recommendations

7.1 Summary

Composite soils are commonly encountered either as natural soils on which engineered earth structures are built, or as reconstituted materials used in engineered fill and soil stabilization, e.g. in engineered liners for landfills. The basic concept of composite soils is known, however, studies performed on these materials are limited. This research has experimentally investigated the hydraulic, thermal and electrical conductivity of a wide range of composite sand-clay mixtures. The ultimate goal was to increase the understanding of composite soils behaviour and to establish a coherent framework for supporting the design and construction of conductivity related geotechnical projects by establishing correlations between a soil's composition and physical properties, and its conductivity.

The research was organized into three main parts. The first part provided a review of composite soils in the context of the classification and engineering behavior schemes. This was followed by an extensive review of the hydraulic, thermal and electrical conductivity of soil, the factors that are expected to influence them, and the methods used to assess and predict them. The relationships between a potential difference, whether it is hydraulic head, temperature or voltage, and flow rate are similar and it is concluded that the coefficients of conductivity are affected by the soil composition, its physical characteristics and environmental factors.

To achieve the research aims and to test the hypotheses that resulted from the literature review, all conductivities had to be measured and analysed on a wide range of composite soils consisting of five types of clays; kaolinite, bentonite, illite, sepiolite, and attapulgite and three types of sands; fine, medium and mixed sand. Two pieces of equipment were designed to determine the conductivities of saturated composite soils which contained various particle types and sizes. The first piece of equipment was designed to comply with the assumptions of Terzaghi for one-dimensional consolidation to determine the hydraulic conductivity indirectly. The second one was designed to determine the hydraulic, thermal and electrical conductivities directly using the principles of Darcy, Fourier, and Ohm. Both equipment proved to be effective, providing consistent results when comparing the data to those obtained from other laboratory investigations and published models. This was the second part.

The third part of the thesis research has covered the interpretation of the test results and an analysis of the factors that influenced the consolidation, hydraulic, thermal and electrical conductivity of a range of composite soils. Conclusions were drawn from the results analysis and are presented in the next section. In general, the results show that the composition of a soil and the properties of the soil particles and pore water have a profound impact on the soil's conductivities to the extent that it is possible to predict the conductivity of a soil with some confidence if its composition is known.

7.2 Conclusions

7.2.1 Index and electro-chemical properties of composite soils

- An increase of sand content (S_m) in composite soils implies that both the liquid limit and plastic limits decrease and the relationships between the limits and sand content is linear for all composite soils up to 70% sand content but the slope depends on the clay type. This means that the consistency limits of composite soil mixtures are entirely governed by the content and mineralogy of both the clay and sand in the mixtures.
- In the plasticity chart, as the sand content increases, the data of the composite soils tends to move towards the T-line, a line around which the limits of composite glacial soils tend to cluster.
- The activity of any specific type of composite soil mixture varies little with the sand content. This can be attributed to the fact that an increase in sand content results in a reduction in the plasticity index (PI) and a reduction in the % clay less than 2mu; in effect, cancelling out the effects.
- There is a direct relationship between specific surface area (A_s) and clay content (C_m) for all composite soil mixtures in that an increase in clay content implies an increase in surface area. For a given clay content, the

specific surface area of bentonite is the highest and kaolinite is the lowest amongst the five clays tested. The specific surface area of sands, at clay content of zero, is very small and, in most cases, it can be neglected. This confirms that the specific surface area of the mixtures is a function of the amount and type of clays in the mixtures.

- Similar to the specific surface area, the cation exchange capacity (CEC) of composite soils increases linearly with increasing clay content, the slope depending on clay type. Thus, CEC could be a good indicator of the amount and type of clay in soils. In the absence of data of the cation exchange capacity, *CEC*, of composite soils, it is possible to predict it with some confidence using the specific surface area, A_s.
- Increasing the liquid limit of soils leads to an increase in the CEC.
- For pure clays, there is a relationship between CEC and activity (A) but for composite soil mixtures, however, the relationship is poor.

7.2.2 Consolidation characteristics of composite soils

- Under the consolidation process, composite soils can be divided into matrix dominated soils in which the electrochemical inter particle relationships of the clay content dominate the behaviour and clast dominated soils in which the inter particle contact forces of the sand content dominate the behaviour.
- The distinction between matrix dominated and clast dominated soils depends on the sand content, the initial conditions, the density of the soil, and the confining effective stress. The transition from a matrix dominated soil to a clast dominated soil occurs when the sand content is between 58% and 85% depending on the clay mineralogy and confining stress.
- The consolidation characteristics of matrix (clay-) dominated soils are a function of the matrix void ratio, a density parameter expressed as the void ratio in terms of the fine grained content, and the activity of the clays.
- There is a relationship between the compression index, the void ratio at the liquid limit, and the void ratio at a confining stress of 100kPa which confirms that this index is a function of the clay mineralogy and the density.

- The coefficient of volume compressibility is a function of either the dry unit weight or the effective stress with the coefficients being a function of the liquid limit.
- The stiffness of clast dominated soils is a function of the confining stress

7.2.3 Hydraulic conductivity of composite soils

- The results of the hydraulic conductivity of composite soils illustrate, as would be expected, that the hydraulic conductivity increases when the global void ratio and stress increase and when the density decreases.
- There is a transition in the hydraulic conductivity behaviour from matrix dominated to clast dominated composite soils which occurs at between 20% and 35% sand content depending on the confining stress and size of fine grained particles. In matrix dominated soils, the permeability is controlled by the characteristics of the clay component. The sand content has little effect on the conductivity as the particles are randomly distributed through the clay matrix. As the clay content reduces, the number of active contacts between the sand particles increases, leading to an increase in the size of pores contained within the soil matrix, thus increasing the permeability. This is the transition zone where the hydraulic conductivity starts to increase. With a further reduction in clay content, the hydraulic conductivity of the soil continues to increase until the flow is dominated by the characteristics of the sand fabric as the influence of the clay content on the flow of water is small and can be ignored. The soil in this zone is non-plastic.
- There is a relationship between hydraulic conductivity of composite soils and void ratio. For matrix dominated soils, the relationship is a function of clay type (expressed by activity) and matrix void ratio; for clast dominated soils, it is a function of particle size and intergranular void ratio.
- A comparison between the indirect values of hydraulic conductivity ($k_{h\text{-}indirect}$) calculated from the consolidation tests and those measured directly ($k_{h\text{-}direct}$) using the new conductivity cell shows that in all composite fine sand-kaolinite mixtures, the calculated indirect hydraulic conductivity values are one to two order of magnitude less than the directly measured values, and

the discrepancy increases as the sand content increases. At a given matrix void ratio, the ratio of ($k_{h\text{-}indirect} / k_{h\text{-}direct}$) ranges from (0.55) for pure kaolinite to (0.034) for fine sand-kaolinite mixture with kaolinite content of 20%.

7.2.4 Thermal conductivity of composite soils

- When applying a constant power of (3.624 W), the increase in temperature in sands generally exceeded that for clays and the time needed to reach the maximum temperature was shorter for sands than for clays. The temperatures reached a maximum after 19, 23, 19, 26, 24 hrs in case of kaolinite, bentonite, illite, sepiolite and attapulgite clays and after 20, 19, 17 hrs for fine, medium and mixed sands, respectively. This is because sands particles have a higher thermal conductivity than clays and thus heat will transfer through them more rapidly.
- An increase in sand content causes an increase in thermal conductivity of the composite soils because the thermal conductivity of the sand particles exceeds that of clay minerals. Initially and when the sand content is less than 20%, the bulk thermal conductivity of the soils is dominated by the conductivity of the clay as the sand particles are distributed through the clay matrix and not in contact with each other. As the sand content increases, the sand particles become closer together until they come in contact. At that point, the thermal conductivity of the soil mixture will be controlled by the conductivity of sand and clay. This is shown for all mixtures with a sand content less than 80%. An increasing sand content increases the thermal conductivity of the soil until it is dominated by the sand conductivity alone as the clay grains have very little effect. This results in a nonlinear relationship between thermal conductivity and sand content.
- The thermal conductivity of composite soils is not only affected by the sand content but is also affected by the particle size of the sand used. At a certain porosity, the thermal conductivity of mixed sand is slightly higher than that of medium and fine sands. This suggests that as the mean particle size of sand increases, the volume of sand particles per unit soil

volume increases and the resistance to heat flow decreases, and therefore, the thermal conductivity increases.

- The transitional behaviour from matrix-dominated to clast-dominated composite soils in thermal conductivity depends not only on the sand content and particle size alone but also on the clay mineralogy and the initial conditions.
- The conductivity of a clay reduces as the liquid limit of the soil increases which is linked with the particle size suggesting that the thermal conductivity depends also on the clay minerology.
- The thermal conductivity of composite soils increases as the water content decreases and soil density increases. This can be attributed to the fact that in saturated soils, the majority of the heat transfers through the higher conductive solid particles and their contact points rather than the water contained in pore spaces. Consolidating the soil reduces the water content and increases the soil’s density thus increasing the effect of the solid particles which have a higher thermal conductivity. As the amount of solids per volume unit is increased, the value of thermal conductivity is increased.
- An increase in porosity based matrix void ratio and in porosity based intergranular void ratio lead to a reduction in the thermal conductivity. Unlike hydraulic conductivity, there is no simple relationship between the thermal conductivity and porosity based on the matrix void ratio and that based on the intergranular void ratio.
- A comparison between the measured values of the bulk thermal conductivity of composite soils and those estimated by Johansen’s model using Gemant’s constants for thermal conductivity of solid particles, underestimates the values with *RMSE* of 0.31 suggesting that the constants of Gemant, and, possibly, the fact that they are only based on the clay content, are not appropriate to estimate the bulk thermal conductivity of composite soils.
- A comparison between the measured values of the bulk thermal conductivity of composite soils and those estimated by Johansen’s model using Johansen’s concept for thermal conductivity of solid particles

shows that they provide a better estimate specifically for composite soils of high sand content, however, there is still a discrepancy with *RMSE* = 0.26. This may be because of the unrepresentative values of the thermal conductivity of solid particles that were used for clays (2 and 3 W/m °C) and sands (7.7 W/m °C).

- In composite saturated sand-clay soils, the bulk thermal conductivity (k_T) can be determined from the thermal conductivity of soil's constitutes (clay, sand, and water) using more representative values determined from tests on pure clays and clean sands; 7.0 for fine sand, 7.1 for medium sand, 7.4 for mixed sand, 3.6 for kaolinite, 3.3 for bentonite, 3.0 for illite, 3.5 for sepiolite, 3.4 W/m °C for attapulgite, and their volumetric fractions in the whole soil using the generalized geometrical mean.

7.2.5 Electrical conductivity of composite soils

- In the voltage-current profile, bentonite was seen to have the lowest resistance (R ≈ 76 Ohm) to the current flow and kaolinite (R ≈ 957 Ohm) the highest value. Sands have a very high electric resistance of more than 5000 Ohm.
- Results on composite soils prepared with tap water of low electrical conductivity reveal that there is either a direct or inverse relationship between the overall soil electrical conductivity (σ_T) and porosity (n) depending on water conductivity (σ_w) and clay particle surface conductivity (σ_s).
- An increase in clay content causes an increase in the overall electrical conductivity of composite soils because of the effect of the negative charges available on the surface of the clay particles as they provide a path other than the pore fluid for current to flow.
- An increase in porosity based matrix void ratio and in porosity based intergranular void ratio lead to either a reduction or an increase in the overall soil electrical conductivity. Unlike hydraulic conductivity, there is no simple relationship between the electrical conductivity and porosity based on the matrix void ratio and that based on the intergranular void

ratio indicating that the concept of matrix and intergranular void ratios could not be useful for interpreting the results of electrical conductivity in composite soils.

- The electrical results in this study show that a soil mixture prepared with tap water of low electrical conductivity having higher cation exchange capacity (CEC) and specific surface area (As) (i.e. bentonite) will display a higher electrical conductivity than a soil with lower CEC and As (i.e. kaolinite, sand) at the same porosity.
- In composite sand-clay soils, the overall electrical conductivity (σ_T) can be modelled as a parallel function of two main components; bulk pore fluid conductance (E_w) and clay minerals conductance (E_s) within the soil that are dependent on the conductivity of fluid (σ_w) and clay particle surfaces (σ_s), respectively, and their volumetric fractions.
- The majority of the composite soils show that, if they have clay conductance, E_s, exceeding that of the tap bulk water, E_w the relevance contribution of their particle surface in electricity transfer is indicated.
- A comparison between the measured values of the overall electrical conductivity of composite soils and those predicted by Waxman and Smits (1968) and Sen et al. (1988) models shows that they work well with clean sands and composite soils of low clay content (e.g. those having low CEC and As). However, for composite soils of high clay content prepared with tap water of low electrical conductivity (those that have high clay surface conductivity and low water conductivity), these models are not valid for estimating the overall electrical conductivity.
- It is possible to extend the concept of Archie’s law that captures the effect of water conductance component to work with clayey soils by including the contribution of clay conductance.
- It has been seen that the clay conductance (E_s) can be obtained from the cation exchange capacity (*CEC*) and the volumetric fraction of clay (x_{caly}) in the whole soil.

7.3 Overall conclusions

- Composite soils can be divided into matrix (clay) dominated soils in which the electro-chemical inter particle relationships of the clay content dominate the behaviour and clast (sand) dominated soils in which the inter particle contact forces of the sand content dominate the behavior.
- Unlike soil classification for engineering purposes that depends only on the particle size, the transition zone between matrix and clast soils in the scheme for engineering behavior depends on the sand to clay content ratio, the initial conditions, the confining stress at the point at which the property was determined, clay mineralogy, particle size distribution and shape. Under a consolidation pressure of up to 1280 kPa, the transition zone for all composite soils used occurs when the sand content is between 58% – 85%. In hydraulic conductivity, it happens when the clay content is between 20% – 35%. Data on the thermal and electrical conductivity shows that the transition behavior is not so well defined but it is the sand particles that dominate the mass behavior when its content exceeds 65% – 78%.
- Increasing sand content reduces the compression index, increases the hydraulic and thermal conductivity and reduces the electrical conductivity.
- Increasing soil particle size leads to an increase in all the soil's conductivities.
- There is a relationship between hydraulic conductivity of composite soils and void ratio. For matrix dominated soils, the relationship is a function of clay type (expressed by activity) and matrix void ratio; for clast dominated soils, it is a function of particle size and intergranular void ratio.
- For practical purposes, it is possible to use the geometrical mean method to predict the bulk thermal conductivity of a soil with a high confidence if its composition is known. The values of the thermal conductivity of the solid particles are k_s; 7.0 for fine sand, 7.1 for medium sand, 7.4 for mixed sand, 3.6 for kaolinite, 3.3 for bentonite, 3.0 for illite, 3.5 for sepiolite, 3.4 W/m ^{o}C for attapulgite.
- To account for the contribution of high clay content and type on the overall soil electrical conductivity at condition of low salinity, new models were established focusing on the clay and water conductance.

7.4 Recommendations

A number of key topics with different subjects have been raised from this study. These are arranged as follow:

- The study on composite soils in this research has provided a good source of data for a better understanding the behaviour of such materials. However, further experiments and numerical investigations on other different compositions of soils in dry and partially saturated conditions are required to assess their mechanical, hydraulic, thermal and electrical properties. For example, it would be good to investigate a combination of clay minerals and sands and also investigate clays with different sizes of sands and gravels not only on reconstituted samples but also on natural composite depositions. This will help in validating the models proposed in this research and show that they can be considered a universal approach for estimating the conductivity of composite soils from their composition and physical characteristics.
- The conductivity equipment that was developed to determine the hydraulic, thermal and electrical conductivity of soils can be used to investigate coupled flow through soils by applying more than one potential. For instance, it is necessary to investigate the effect of flowing water flow on the heat and current transfer in soils, or to investigate the effect of heat transfer on the flow of water and electricity in soils due to their importance in a number of engineering applications (e.g. in energy piles, ground source heat pump, GSHPs, soil's treatment by electro-osmosis). This should give sets of data which can be used to validate the existing numerical models of coupled flow.
- It would be interesting to establish whether there is a relationship between the hydraulic, thermal and electrical conductivity given that they are influenced by similar soil properties. If relationships do exist, then it would be possible to predict the electrical and thermal conductivity from the more readily available hydraulic conductivity.

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