

Experimental Investigation of Thermal Conductivity of
Soils and Borehole Grouting Materials



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Declaration

I, Abdulbaset Ahmed Alrtimi, declare that the thesis entitled *Experimental Investigation of Thermal Conductivity of Soils and Borehole Grouting Materials* and the work presented in the thesis are my own, and have been generated by me as the result of my own original research.

Signed: -----

Date: 12th of November 2014

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Abstract

Exploitation of thermogeology energy in heating and cooling of buildings starts to spread worldwide as an alternative renewable source of heat energy. The thermal conductivity of soils is among the critical parameters required to achieve a proper design of ground heat exchangers or any underground systems that involve thermo-active processes. This research is a part of study related to the laboratory measurements of thermal conductivity of soils and thermal grouts used for borehole heat exchangers.

The first part of this project involves a design of a new thermal cell that can be used to measure the thermal conductivity of soils. The design of the apparatus is based on the application of Fourier's law at steady state condition where unidirectional heat flux is generated through two identical specimens. A new concept of minimizing the radial heat losses that occur due to the ambient temperature interface (ATI) using a thermal jacket as a heat insulation barrier has been introduced in the design and experimentally performed. The obtained results and the analysis of the heat flow reveal that the longitudinal heat flow can be maximized and the radial heat flow can be minimized when the thermal jacket is used with proper temperature control. Also, it has been revealed that the measured thermal conductivity of soils is sensitive to further boundary conditions such as thermocouples and temperature of sink disks. In addition to its simplicity, the new cell can be used for undisturbed field samples (U100 samples) as well as laboratory-prepared specimens. The sample preparation and the test procedure for the two different soil conditions highlighted the simplicity of using the new apparatus in measurement of the thermal conductivity of soils.

The second part of this research concerns a production of new thermal grout for borehole heat exchangers using unwanted industrial and domestic materials (PFA and ground glass-low cost) and the commodity fluorspar, all of which have relatively high thermal conductivity. The thermal conductivity of different PFA based grouts that comprise different enhancing materials at different mix proportions has been measured dry and at saturation using the new thermal cell. The results highlighted the effect of mineralogy and the particle size distribution

of the mix constituents on the thermal conductivity of the grout. The results showed that a combination of fluorspar with coarse ground glass can provide good thermal enhancement in both dry and saturated conditions. The grout that consist of 20% cement, 30% PFA, 15% coarse ground glass and 35% fluorspar by weight with dry and saturated thermal conductivity of 1.283 and 1.985 $W/m.K$ respectively can be considered as a suitable grout that can be used successfully in UK. Comparing with thermally enhanced bentonite (1.46 $W/m.K$), it is expected that with London Clay Formation optimal performance of borehole heat exchangers and cost savings would be achieved using the selected grout.

The work done in the final part can be considered as an application of the new steady state thermal cell in the estimation of the thermal conductivity of sandy soils. Also, it can be considered as a case study where the thermal conductivity was measured for soils that have not been previously thermally tested (Tripoli sand). The effects of the porosity and degree of saturation on the thermal conductivity of Tripoli sand were investigated. The results of twenty experimental tests showed that the effect of the saturation degree is significant compared with the effect of dry density especially at saturation degree less than 10%. Also, the results revealed that the thermal conductivity is approximately linearly proportional to the dry density at all levels of saturation. The validation of some existing selected prediction models showed that none of the selected models is able to correctly match the thermal conductivity of Tripoli sand at all conditions. However, some models were more accurate than others in certain conditions. It is also concluded that all presented models failed to estimate the thermal conductivity of such soil in low or partially saturated conditions where convection started to play a role in the heat transfer mode. On the other hand, the variation of thermal conductivity of Tripoli sand can be fittingly described as logarithmic function of the water content at all levels of porosity with R^2 value ranges between 0.9694 and 0.9732. As a result, an empirical model based on the experimental results expressing the thermal conductivity in terms of water content and porosity has been obtained and validated.

Table of Content

DECLARATION	I
ACKNOWLEDGEMENT	II
ABSTRACT	III
TABLE OF CONTENT	V
LIST OF FIGURES	XI
LIST OF TABLES	XV
LIST OF SYMBOLS	XVI
CHAPTER 1 : INTRODUCTION	1
1.1 RATIONALE AND BACKGROUND	1
1.2 GROUND SOURCE HEAT PUMP SYSTEMS	4
1.3 THERMAL RESISTANCE OF BOREHOLE HEAT EXCHANGER	6
1.4 THERMAL RESPONSE TEST (TRT)	6
1.5 HEAT TRANSFER THROUGH SOILS	7
1.6 THERMAL CONDUCTIVITY OF SOILS	8
1.7 STEADY STATE LABORATORY MEASUREMENTS	9
1.8 UNSTEADY STATE LABORATORY MEASUREMENTS	10
1.9 THESIS AIM AND OBJECTIVES	11
1.10 SCOPE OF THE THESIS	12
1.10.1 Chapter one (introduction)	12
1.10.2 Chapter two (literature review)	12
1.10.3 Chapter three (Steady-state thermal conductivity apparatus)	13
1.10.4 Chapter four (Thermal enhancement of pulverized fuel ash (PFA)- based grout)	13
1.10.5 Chapter five (Thermal conductivity of Tripoli sand)	14
1.10.6 Chapter six (conclusions and recommendations)	14
CHAPTER 2 : LITERATURE REVIEW	15
2.1 INTRODUCTION	15
2.2 THERMAL ENERGY, HEAT AND TEMPERATURE	15
2.2.1 Thermal energy	15
2.2.2 Heat	15

2.2.3	Temperature.....	16
2.3	FORMS OF HEAT TRANSFER	16
2.3.1	Conduction.....	16
2.3.2	Convection	18
2.3.3	Radiation	19
2.4	THERMAL PROPERTIES OF SOILS	19
2.4.1	Thermal conductivity of soils	20
2.4.2	Heat capacity of soils	20
2.4.3	Thermal diffusivity of soils	22
2.5	FACTORS INFLUENCING THERMAL PROPERTIES OF SOILS	22
2.5.1	Influence of moisture content	22
2.5.2	Influence of dry density.....	24
2.5.3	Influence of soil constituents	25
2.5.4	Influence of soil structure or texture.....	26
2.5.5	Influence of particle size.....	27
2.5.6	Influence of temperature	28
2.6	Field thermal CONDUCTIVITY MEASUREMENTS	29
2.7	LABORATORY THERMAL CONDUCTIVITY MEASUREMENTS.....	30
2.7.1	Steady state experimental techniques.....	31
2.7.1.1	Hot plate methods	31
2.7.1.1.1	The guarded hot plate (GHP).....	32
2.7.1.1.2	Unguarded hot plate method.....	34
2.7.1.1.3	Heat flow meter apparatus	34
2.7.1.1.4	Guarded comparative – longitudinal heat flow technique... 35	
2.7.1.1.5	Concentric cylinder method.....	36
2.7.1.1.6	Concentric spheres method	37
2.7.2	Transient state methods.....	38
2.7.2.1	Transient hot wire method	38
2.7.2.2	Thermal Needle Method (single probe).....	39
2.7.2.3	Dual Probe Method.....	40
2.8	PREDICTION METHODS	41
2.9	BOREHOLE THERMAL RESISTANCE	44
2.10	THERMAL GROUTS.....	45
2.10.1	Enhancement of thermal conductivity of grout.....	45

2.10.2 Permeability.....	46
2.10.3 Groutreology flow.....	47
CHAPTER 3: STEADY-STATE THERMAL CONDUCTIVITY;NEW APPARATUS ..	49
3.1 INTRODUCTION	49
3.2 DESIGN AND DESCRIPTION.....	50
3.2.1 Basic concepts.....	50
3.2.2 Factors controlling the design	52
3.2.2.1 Unidirectional heat flow.....	52
3.2.2.2 Base heat loss	52
3.2.2.3 Heat uniformity	53
3.2.2.4 Thermocouples	53
3.2.2.5 Specimen length	53
3.2.3 Apparatus description.....	53
3.2.3.1 The acrylic body.....	54
3.2.3.2 The heater disc	54
3.2.3.3 Sink discs	55
3.2.3.4 The thermal jacket.....	55
3.2.3.5 Thermocouples	56
3.2.3.6 Water circulation system.....	56
3.2.3.7 TC-08 Pico-logger	57
3.2.3.8 DC current source	57
3.2.3.9 Steel holder plates.....	57
3.2.3.10 Constant temperature room	58
3.3 SPECIMEN PREPARATION AND PROCEDURES.....	58
3.3.1 Field samples (undisturbed samples).....	58
3.3.2 Reconstituted samples	59
3.3.2.1 Cohesive soils	59
3.3.2.2 Non-Cohesive soils.....	60
3.3.3 Test set-up and procedure.....	62
3.3.3.1 Placing of specimens	62
3.3.3.2 Power input selection	63
3.3.3.3 Thermocouples, Pico-logger and water pump	63
3.3.3.4 Starting the test.....	65

3.3.3.5	Calculations and correction method	65
3.4	EXPERIMENTAL ASSESSMENT	67
3.4.1	Heat distribution in the specimen	67
3.4.2	Effect of thermocouples configuration	67
3.4.3	Effect of natural and forced convection on sink discs	68
3.4.4	Effect of thermal jacket	69
3.4.5	Apparatus performance using reference material	70
3.4.6	Repeatability and error estimation	70
3.4.7	Comparison with transient probe method	71
3.5	EXPERIMENTAL RESULTS AND DISCUSSION	72
3.5.1	Heat uniformity.....	72
3.5.2	Heat flow analysis.....	73
3.5.3	Thermocouple configuration	76
3.5.4	Ideal thermal jacket temperature.....	77
3.5.5	Sink disc temperature.....	79
3.5.6	Apparatus performance using a reference material.....	80
3.5.7	Comparison with transient method	81
3.6	PRACTICAL APPLICATION.....	85
3.6.1	Testing of undisturbed samples	85
3.6.2	Testing of cohesive soils	86
3.7	SUMMARY	87

CHAPTER 4 : THERMAL ENHANCEMENT OF PFA-BASED GROUT FOR

	BOREHOLE HEAT EXCHANGERS.	89
4.1	INTRODUCTION	89
4.2	MATERIAL	91
4.2.1	Pulverized Fuel Ash (PFA)	91
4.2.2	Cement	91
4.2.3	Ground Glass	93
4.2.4	Coarse Sand	93
4.2.5	Fine Sand	94
4.2.6	Fluorspar	94
4.3	MIX DESIGN	95
4.4	SAMPLE PREPARATION	96

4.5	EXPERIMENTAL TESTING	98
4.5.1	Grout flow	98
4.5.2	Shrinkage	99
4.5.3	Thermal conductivity	99
4.5.4	Permeability	100
4.6	RESULTS AND DISCUSSION	100
4.6.1	Thermal conductivity results	101
4.6.1.1	Grout selection	105
4.6.1.2	Comparison with other grouts	106
4.6.2	Permeability	106
4.6.3	Grout flow	107
4.6.4	Shrinkage	108
4.7	SUMMARY	108
CHAPTER 5 : THERMAL CONDUCTIVITY OF TRIPOLI SAND		110
5.1	INTRODUCTION	110
5.2	EXPERIMENTAL METHODOLOGY	111
5.2.1	Materials.....	111
5.2.2	Steady state thermal conductivity measurement	113
5.2.2.1	Sample preparation	113
5.2.2.2	Test procedure	115
5.2.3	Transient probe method (KD2)	117
5.3	EXPERIMENTAL RESULTS	118
5.4	PREDICTION METHODS	119
5.4.1	De Vries equation (1963)	119
5.4.2	Johansen method (1975)	121
5.4.3	Donazzi et al. model (1979).....	122
5.4.4	Gangadhara Rao and Singh (1999).....	123
5.4.5	Côté and Konrad (2005).....	124
5.4.6	Lu et al. model (2007).....	125
5.4.7	Chen (2008)	126
5.4.8	Haigh (2012).....	127
5.5	RESULTS DISCUSSION	129
5.5.1	Steady state results versus transient state results	129

5.5.2	Experimental results versus prediction method results	131
5.5.3	Effect of dry density	136
5.5.4	Effect of degree of saturation	137
5.6	THE PROPOSED EMPIRICAL MODEL FOR TRIPOLI SAND	139
5.7	SUMMARY	142
CHAPTER 6 : CONCLUSIONS AND RECOMMENDATIONS.....		144
6. 1	THE NEW STEADY STATE THERMAL CELL	145
6. 2	THERMAL ENHANCEMENT OF PFA- BASED GROUT.....	148
6. 3	THERMAL CONDUCTIVITY OF TRIPOLI SAND	150
6. 4	RECOMMENDATIONS FOR FURTHER RESEARCH	151
PUBLICATIONS.....		154
REFERENCES		155

List of figures

FIGURE 1-1 : (A) CLOSED LOOP SYSTEM (B) OPENED LOOP SYSTEM	5
FIGURE 1-2 : HEAT TRANSFER PATHS IN MASS MATERIALS.....	7
FIGURE 2-1 : UNIDIRECTIONAL CONDUCTION HEAT TRANSFER	17
FIGURE 2-2 : TYPES OF BOND BETWEEN PLATE-LIKE CLAY PARTICLES	27
FIGURE 2-3 : PRINCIPLE CHARACTERISTICS OF GHP APPARATUS	33
FIGURE 2-4 CONFIGURATION OF TWO TYPES OF HEAT METER APPARATUS	35
FIGURE 2-5 : SCHEMATIC OF GUARDED COMPARATIVE - LONGITUDINAL HEAT FLOW SYSTEM.....	36
FIGURE 2-6 : SCHEMATIC OF CONCENTRIC CYLINDER METHOD.....	36
FIGURE 2-7 : SCHEMATIC OF CONCENTRIC SPHERES METHOD	37
FIGURE 3-1 : SCHEMATIC DIAGRAM OF THE NEW THERMAL CELL	51
FIGURE 3-2 : (A) THE INSULATING CYLINDER (B) THE SPECIMEN CYLINDER	54
FIGURE 3-3 : (A) SINK DISC (B) THERMAL JACKET	56
FIGURE 3-4 : (A) WATER CIRCULATING SYSTEM (B) TC-08 PICO-LOGGER	57
FIGURE 3-5 : (A) DC CURRENT SOURCE (B) STEEL HOLDER PLATES.....	58
FIGURE 3-6 : SPECIMEN CYLINDERS CONTAINING UNDISTURBED FIELD SAMPLES	59
FIGURE 3-7 : THE CONSOLIDATION CELL	60
FIGURE 3-8 : SPECIMEN CYLINDERS CONTAINING SAND SAMPLES.....	62
FIGURE 3-9 : PLACING OF SPECIMENS INTO THE THERMAL CELL	62
FIGURE 3-10 : SIX THERMOCOUPLES INSERTED TO THE SPECIMEN CENTRE	64
FIGURE 3-11 : COMPLETE SET-UP OF THE THERMAL CONDUCTIVITY TEST APPARATUS	64
FIGURE 3-12 : TYPICAL TEMPERATURE VERSUS TIME PROFILE.....	65
FIGURE 3-13 : AN EXAMPLE OF THERMAL CONDUCTIVITY CORRECTION METHOD	66
FIGURE 3-14 : THERMAL CONDUCTIVITY USING SINGLE PROBE METHOD (KD2)	71
FIGURE 3-15 : TEMPERATURE PROFILE OF THREE LATERAL POINTS.....	72
FIGURE 3-16 : TEMPERATURE PROFILE ALONG THE SPECIMEN LENGTH.....	73
FIGURE 3-17 : EFFECT OF THERMAL JACKET TEMPERATURE	75
FIGURE 3-18 : THERMAL CONDUCTIVITY MEASURED USING ONE MOBILE THERMOCOUPLE AND THREE FIXED THERMOCOUPLES	76
FIGURE 3-19 : THERMAL CONDUCTIVITY MEASURED USING LONGITUDINAL AND LATERAL THERMOCOUPLES.....	77
FIGURE 3-20 : DETECTION OF IDEAL THERMAL JACKET TEMPERATURE.....	78

FIGURE 3-21 : EFFECT OF FORCED CONVECTION ON TEMPERATURE PROFILE.....	79
FIGURE 3-22 : EFFECT OF FORCED CONVECTION ON THERMAL CONDUCTIVITY	80
FIGURE 3-23 : REPEATABILITY OF RESULTS FOR FINE SAND SAMPLE	81
FIGURE 3-24 : THERMAL CONDUCTIVITY RESULTS OBTAINED USING STEADY AND TRANSIENT STATE METHODS AT DIFFERENT CONDITIONS	82
FIGURE 3-25 : RELATIVE DIFFERENCE IN THE THERMAL CONDUCTIVITY VALUES OBTAINED BY THE NEW STEADY STATE APPARATUS AND THE PROBE METHOD	83
FIGURE 3-26 : KD2 RESULTS USING DIFFERENT TEST DURATIONS.....	84
FIGURE 3-27 : UNDISTURBED GLACIAL TILL SAMPLES PREPARED FOR TESTING.....	85
FIGURE 4-1 : (A) PULVERIZED FUEL ASH (PFA) (B) GENERAL PURPOSE PORTLAND CEMENT.....	92
FIGURE 4-2 : GROUND GLASS: (A) RAW (B) COARSE SIZE (C) MEDIUM SIZE (D) FINE SIZE	93
FIGURE 4-3 : (A) COURSE SAND (B) FINE SAND	94
FIGURE 4-4 : FLUORSPAR	94
FIGURE 4-5 : WATER CURING OF GROUT SPECIMENS	97
FIGURE 4-6 : FLOW TEST APPARATUS.....	98
FIGURE 4-7 : SHRINKAGE MEASUREMENT USING BRASS MOULDS	99
FIGURE 4-8 : PLOT OF THERMAL CONDUCTIVITY PFA- BASED GROUT VERSUS PERCENTAGE OF (A) COARSE SAND AND (B) FLUORSPAR.....	102
FIGURE 4-9 : PLOT OF THERMAL CONDUCTIVITY PFA- BASED GROUT VERSUS PERCENTAGE OF FLUORSPAR + COARSE GROUND GLASS.....	103
FIGURE 4-10 : PLOT OF THERMAL CONDUCTIVITY PFA- BASED GROUT VERSUS (A) FINE SAND (B) MEDIUM GROUND GLASS (C) COARSE GROUND GLASS (D) MIXED GROUND GLASS.	104
FIGURE 5-1 : DRY TRIPOLI SAND SAMPLE	111
FIGURE 5-2 : GRAIN SIZE DISTRIBUTION FOR TRIPOLI SAND	112
FIGURE 5-3 : TWO SPECIMEN CYLINDERS WITH SOIL SAMPLES	115
FIGURE 5-4 : TYPICAL TEMPERATURE VERSUS TIME CURVE	116
FIGURE 5-5 : THERMAL CONDUCTIVITY MEASUREMENT USING KD2 INSTRUMENT.....	117
FIGURE 5-6 : PLOTS OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING DE VRIES (1963) MODEL ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND.....	120

FIGURE 5-7 : PLOTS OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING JOHANSEN (1975) MODEL ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND.....	122
FIGURE 5-8 : PLOTS OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING DONAZZI (1979) MODEL ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND.....	123
FIGURE 5-9 : PLOTS OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING RAO & SINGH (1999) MODEL ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND.....	124
FIGURE 5-10 : PLOTS OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING COTE & KORNAD (2005) MODEL ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND.....	125
FIGURE 5-11 : PLOTS OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING LU ET AL. (2007) MODEL ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND.....	126
FIGURE 5-12 : PLOTS OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING CHEN (2008) MODEL ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND.....	127
FIGURE 5-13 : PLOTS OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING HAIGH (2012) MODEL ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND.....	128
FIGURE 5-14 : THERMAL CONDUCTIVITY RESULTS OF TRIPOLI SAND USING STEADY STATE AND TRANSIENT STATE METHODS	129
FIGURE 5-15 : COMPARISON OF STEADY STATE ON TRANSIENT STATE THERMAL CONDUCTIVITY RESULTS OF TRIPOLI SAND	130
FIGURE 5-16 : PLOT OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING DIFFERENT PREDICTION MODELS ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND AT POROSITY OF 0.494	132
FIGURE 5-17 : PLOT OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING DIFFERENT PREDICTION MODELS ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND AT POROSITY OF 0.462	133
FIGURE 5-18 : PLOT OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING DIFFERENT PREDICTION MODELS ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND AT POROSITY OF 0.432	133

FIGURE 5-19 : PLOT OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING DIFFERENT PREDICTION MODELS ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND AT POROSITY OF 0.406	134
FIGURE 5-20 : COMPARISON OF PREDICTED METHODS ON MEASURED STEADY STATE THERMAL CONDUCTIVITY RESULTS OF TRIPOLI SAND.....	135
FIGURE 5-21 : COMPARISON OF PREDICTED METHODS ON MEASURED TRANSIENT STATE THERMAL CONDUCTIVITY RESULTS OF TRIPOLI SAND.....	135
FIGURE 5-22 : PLOT OF EFFECTIVE THERMAL CONDUCTIVITY VERSUS DRY DENSITY OF TRIPOLI SAND AT DIFFERENT DEGREES OF SATURATION	137
FIGURE 5-23 : PLOT OF EFFECTIVE THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION OF TRIPOLI SAND AT DIFFERENT POROSITIES	138
FIGURE 5-24 : PLOT OF EFFECTIVE THERMAL CONDUCTIVITY VERSUS WATER CONTENT OF TRIPOLI SAND AT DIFFERENT POROSITIES.....	138
FIGURE 5-25 : EXAMPLE OF THE LOGARITHMIC RELATION BETWEEN THERMAL CONDUCTIVITY AND WATER CONTENT OF TRIPOLI SAND.....	140
FIGURE 5-26 : COMPARISON OF PROPOSED MODEL ON MEASURED THERMAL CONDUCTIVITY RESULTS OF TRIPOLI SAND.....	141
FIGURE 5-27 : PLOTS OF THERMAL CONDUCTIVITY VERSUS DEGREE OF SATURATION USING THE PROPOSED MODEL ALONG WITH EXPERIMENTAL RESULTS FOR TRIPOLI SAND.....	141

List of tables

TABLE 2-1 : THERMAL CONDUCTIVITY FOR SOME OF SOIL CONSTITUENTS	26
TABLE 3-1 : RESULTS OF TESTING OF UNDISTURBED AND RECONSTITUTED GLACIAL TILL SAMPLES	86
TABLE 4-1 : COMPOSITIONS OF MATERIALS USED IN THIS STUDY, DETERMINED BY X- RAY FLUORESCENCE (DEPARTMENT OF GEOLOGY, UNIVERSITY OF LEICESTER, UK).	92
TABLE 4-2 : DETAILS OF SUGGESTED GROUT GROUPS	96
TABLE 4-3 : DRY AND SATURATED THERMAL CONDUCTIVITY RESULTS FOR PROPOSED GROUTS	101
TABLE 4-4 : PERMEABILITY OF THE SELECTED GROUP (G).....	107
TABLE 5-1 : COMPOSITIONS OF TRIPOLI SAND, DETERMINED BY X-RAY FLUORESCENCE (DEPARTMENT OF GEOLOGY, UNIVERSITY OF LEICESTER, UK).	112
TABLE 5-2 : THEORETICAL DESIGN OF TRIPOLI SAND SPECIMENS	116
TABLE 5-3 : RESULTS OF THERMAL CONDUCTIVITY FOR TRIPOLI SAND.....	118
TABLE 5-4 : VALUES OF THE EMPIRICAL PARAMETERS (A & B).....	140

List of symbols

k	Effective thermal conductivity ($W/m.K$)
k_{dry}	Dry thermal conductivity ($W/m.K$)
k_{sat}	Saturated thermal conductivity ($W/m.K$)
k_s	Thermal conductivity of soil particles ($W/m.K$)
k_w	Thermal conductivity of water ($W/m.K$)
k_a	Thermal conductivity of air ($W/m.K$)
k_f	Thermal conductivity of fluid ($W/m.K$)
C_v	Volumetric heat capacity ($J/m^3.K$)
C_p	Specific heat capacity ($J/Kg.K$)
C_s	Specific heat of soil particles ($J/Kg.K$)
C_w	Specific heat of water ($J/Kg.K$)
C_a	Specific heat of air ($J/Kg.K$)
α	Thermal diffusivity (m^2/s)
Q	Heat energy in joules (J)
q	Rate of heat transfer (Watts) $1 W = 1 J/sec$
A	Cross-sectional area (m)
t	Time (s)
T	Temperature ($^{\circ}C$ or K)
T_i	Initial temperature ($^{\circ}C$ or K)
T_f	Fluid temperature ($^{\circ}C$ or K)
h	Convective heat-transfer coefficient ($W/m^2.K$)
σ	Stefan-Boltzmann constant 5.699×10^{-8} ($W/m^2.K^4$)
M_s	Mass fraction of soil particles (kg)
M_w	Mass fraction of water (kg)
M_a	Mass fraction of air (kg)
V_s	Volume of soil particles (m^3)
V_w	Volume of water (m^3)
V_a	Volume of air (m^3)
V	Total volume (m^3)
γ	Unit weight (N/m^3)
ρ	Density (kg/m^3)

ρ_d	Dry density (kg/m^3)
ρ_w	Water density (kg/m^3)
ρ_{wet}	Wet density (kg/m^3)
n	Porosity
S_r	Degree of saturation
G_s	Specific gravity of the solid particles
e	Void ratio
R_b	Borehole thermal resistance ($m. K/W$)
r	Radius (m)
K	Permeability (m/s)

Chapter 1 : Introduction

This research is a part of study related to the use of the ground as source and storage of thermal energy. The work is focusing on the laboratory techniques used to determine the thermal conductivity of soils. A new thermal cell has been designed and built for this purpose. This cell is to enable tests to be carried out on a variety of soils and grouting material under different conditions.

1.1 Rationale and background

The total size of the world population is projected to increase from its current 7.0 billion to more than 9.0 billion by 2050 (United Nation, 2005). This growth is a principal cause of raising the demand for food, water and energy. Due to the massive environmental damage caused by conventional means of producing energy, it can be considered that energy supply is one of the most important technological challenges facing humanity today. Dependency on fossil fuels to face the energy demand is directly linked with increasing emission of the Green House Gases (GHG) in the atmosphere. The concentrations of the GHGs in the atmosphere increase when removal processes are lesser than emissions. Among a group of long-live Green House gases, carbon dioxide (CO₂) is the most important anthropogenic gas that can significantly increase global warming. The annual emission of CO₂ has dramatically grown during the last few decades, and global warming will continue whatever we do. This is due to the time delay between creating the problem and its visibility. Scientists reported that, the warming of the Earth has been already started and they estimated that, by the year 2100 the Earth temperature will rise about 2.5 °C (Bals and Gengel, 2008). The increasing demands of energy and the need to reduce the emission of CO₂ to fight global warming lead to a great emphasis on energy conservation. The exploration of renewable and sustainable resources of energy is the priority to meet the demand of energy in the future.

Geothermal and Thermogeology energy are receiving growing attention as the demand for cleaner, cheaper and sustainable energy source is increasing by the day. Geothermal energy is energy derived from the interior heat of the earth in volcanic prone areas of the world. Factually it is the heat held inside the earth that produces geological event on a planetary measure (Dickson and Fanelli, 2004). It involves drilling boreholes or wells at a greater depth to tap hot water or steam at very high temperatures for heating or electric power generation. Because this type of energy source is not available everywhere the use of this technology is limited to some few places on earth. On the other hand thermogeology is readily available the world over. Thermogeology is the heat stored in the ground surface gained from the ground, ground water, rivers and streams tapped from the solar system and from the conductive flow of heat from the deep hotter zones to the cooler zones in the surface. Banks 2008 defines the thermogeology as the study of the occurrence, movement and exploitation of low enthalpy heat in the relatively shallow geosphere. It involves the study of so-called ground source heat. This energy is derived from the upper 150 m of the Earth's crust where the temperature is approximately constant throughout the year.

Ground source heat systems make use of the ground as a heat source in winter and a heat sink in summer to provide heating and cooling for buildings. The efficiency of the ground as an energy supply depends entirely on the thermal properties of the ground soil layers. Just as importantly, the thermal resistance of the borehole, which mainly depends on the thermal properties of the grouting material, can significantly influence the efficiency of the GSHP systems. A clear understanding of storage and heat flow through geomaterials is of great interest in many geoen지니어ing applications involving thermal effects for example oil and gas piping, buried high voltage electrical cables, heat exchanger boreholes, energy foundations, ground improvement and nuclear waste repositories (Krishnaiah and Singh, 2003).

Many nations are using the heat stored in the near surface of the ground (thermogeology) as a means of reducing the energy demand for heating and cooling of buildings, because it is generally clean, safe, renewable, sustainable and available at any time. On the other hand, from a strategic point of view,

thermogeology energy is less sensitive to the condition of the international energy market. This will reduce the risk of over reliance on energy that is imported from regions that are not necessarily stable such as the Middle East which is the world's largest oil producer. Therefore, many recent regulatory initiatives by international and local governments are fostering the current boom in demand for GSHP systems. GSHP technology is well established in mainland Europe for domestic use and for commercial buildings. It has been little used in the UK but there is now increasing awareness of the technology as it uses renewable heat resource and because it will become increasingly more economic as gas prices rise. It is recorded that the first use of the energy piles in the UK was in the year 2001 (Suckling and Smith, 2002).

Thermal conductivity is of interest in three different areas. The first area was developed by soil scientists who were interested in the effects of soil temperature on vegetation. The second area of interest was developed by geotechnical engineers who were interested in ground freezing and the effect that this has upon near surface soils. The most recent area of interest has been the use of energy piles in which the ground is used as either a heat source or a heat sink. Soil scientists and geotechnical engineers have used different investigative and design methodologies with different symbols and different methods of interpretation of tests in measuring the same parameters. In all cases the parameters that describe the ability for heat to flow through soil and the capacity of soil to absorb heat are thermal conductivity, heat capacity and thermal diffusivity with the most important being thermal conductivity. Section 2.4 explains each parameter. These properties depend on several factors which can be classified into two broad groups: those which are inherent to the soil itself such as soil texture, mineralogical composition and grain size distribution and those which can be managed externally including water content, temperature and soil bulk density (Abu-Hamdeh et al., 2001). Of all the thermal soil properties, thermal conductivity is the most variable, the easiest to misjudge and hardest to correctly measure (Agab, 2005). It is considered to have a significant effect on controlling the heat transfer through the soil (Nusier and Abu-Hamdeh, 2003).

With this in view, attempts have been made by several researchers to measure the thermal conductivity of different soils in different conditions. Thermal

properties of a soil mass can be measured either in-situ or using laboratory procedures. The common field test to determine the thermal parameters of the underground is the Thermal Response Test (TRT) that was firstly, developed in Sweden and USA in 1995 and is now used in many countries worldwide (Gehlin, 2002). TRT is expensive, time consuming and provides only an average thermal conductivity value along the borehole heat exchanger. Laboratory techniques can be classified into two main groups of methods. The first is steady state methods, which measure the thermal conductivity when the heat flux through the soil reaches a constant level and the temperature of the soil specimen is constant with time at any point. The second uses unsteady state methods, which measure the thermal conductivity during the transient state (Abuel-Naga et al., 2009). It should be noted that the transient state procedures are simpler and quicker to use than steady state. However, the steady–state methods are considered more accurate than the transient methods (Hamuda, 2009).

Numerous analytical and numerical approaches have been developed to model the variation and of thermal conductivity of the soil. These methods vary in applicability and complexity, and can be applied only under certain conditions and limitations. Farouki (1986) studied the applicability of these methods and gave recommendations on the conditions under which each method can be used. Due to the limited experimental results to support these models, one aim of this research work is to produce results that can be used to validate some selected models.

1.2 Ground source heat pump systems

Ground source heat pump (GSHP) systems are relatively new renewable efficient technology for space heating and cooling. It is relying on the fact that the temperature of the Earth at depth of 30m is relatively constant and equal to the average annual temperature of the atmosphere (Esen, 2009). This temperature rises with depth due to high underground temperature. With borehole heat exchangers (BHE) ground source heat pumps can offer both heating in winter and cooling in summer with great flexibility to meet any demand. In heating seasons, heat is removed from the earth through a heat carrier, upgraded by the heat pump and transmitted to indoor space. During the cooling seasons, this

process is reversed, with the heat being extracted from the indoor air and injected into the ground. Compared with conventional means of heating and cooling, GSHP systems have a number of advantages, including high efficiency, low maintenance costs and low life cycle cost. However, the high initial costs of GSHP systems sometimes cause a building owner to reject the GSHP system alternative.

There are two techniques used in the GSHP systems as a heat exchanger. The first is the closed loops system (Figure 1-1a) which can be used in any soil. This system comprises the primary circuit, the heat pump and the secondary circuit. The primary circuit consist of the elements of the system which interacts with the heat source. The secondary circuit comprises the heating and cooling delivery system. The second is open loop system (Figure 1-1b) where the system fed by ground water from a well. This system used only in granular soils in which the permeability is great enough to allow ground water to flow at sufficient rate to fed the system.

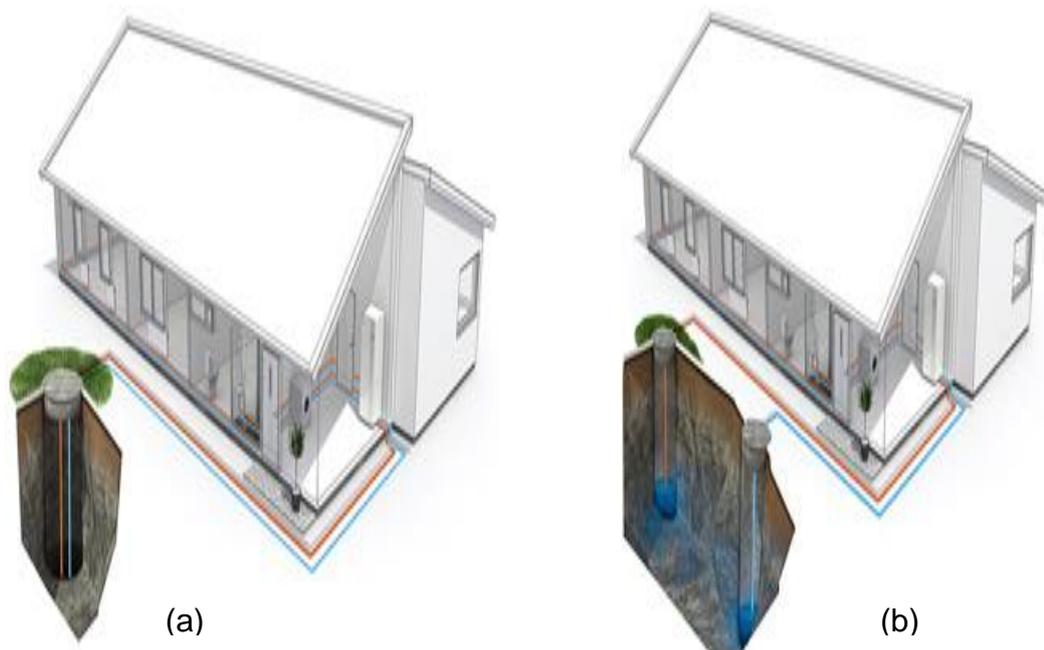


Figure 1-1 : (a) Closed loop system (b) Opened loop system

1.3 Thermal resistance of borehole heat exchanger

The conventional vertical heat exchanger (borehole) consists of three main components. The three components are the water-bearing pipe, grout material around the pipe and soil around the grout. The vertical borehole has a cylindrical shape with different diameters and depths. High density polyethylene (HDPE) plastic pipe is usually used with diameter ranges from 20mm to 40mm. It is inserted in a “U” shape, with a “U-bend” at the bottom of the borehole. The next component is the material surrounding the pipe, usually grout, which plays an important role in heat transfer between the soil and the heat carrier. Different grouting materials with different values of thermal conductivity, typically ranging from 0.5 to 1.6 $W/m.K$ are used (AUSTIN, 1998). In closed-loop vertical heat exchangers, one of the most important factors that influence the efficiency of the system is the thermal resistance of the borehole which is related to the thermal properties of the backfill material. Conventional bentonite grouts have been shown to represent the main thermal resistance (65%) followed by the HDPE tube wall (35%) (Delaleux et al., 2012). Therefore the efficiency of the ground heat exchanger can be improved by increasing the thermal conductivity of the grout.

One aim of this research is to produce a thermal grout using unwanted material (pulverised fuel ash (PFA) and ground glass) with relatively high thermal conductivity to enhance the performance of the borehole heat exchanger.

1.4 Thermal response test (TRT)

The proper design of the boreholes (length, spacing and number) is highly dependent upon the thermal characteristics of the soil. An important development to determine the thermal parameters of the ground in situ is the thermal response test (TRT) that was first developed in Sweden and USA in 1995 and now is used in many countries worldwide (Gehlin, 2002). The thermal response test is an effective method to determine the ground’s thermal properties. A known thermal load is injected into a borehole heat exchanger and accurate measurements of the inlet and outlet temperatures of the circulating fluid are recorded. In general, TRT provides only an average thermal conductivity value along the borehole heat exchanger. The analysis of the experiment is based on the line heat source

approach which involves many assumptions. The error can vary by $\pm 10\%$ which is accepted for an appropriate prediction for thermogeology heat yield (Wagner and Clauser, 2005). More details are presented in section 2.6.

1.5 Heat transfer through soils

Soils consist of solid particles surrounded by pore space. This pore space is generally filled with air (dry soil) or liquid (water; saturated soil) or by both air and water (partially saturated soil). Figure 1-2 shows the heat transfer paths that can be exist in soil mass.

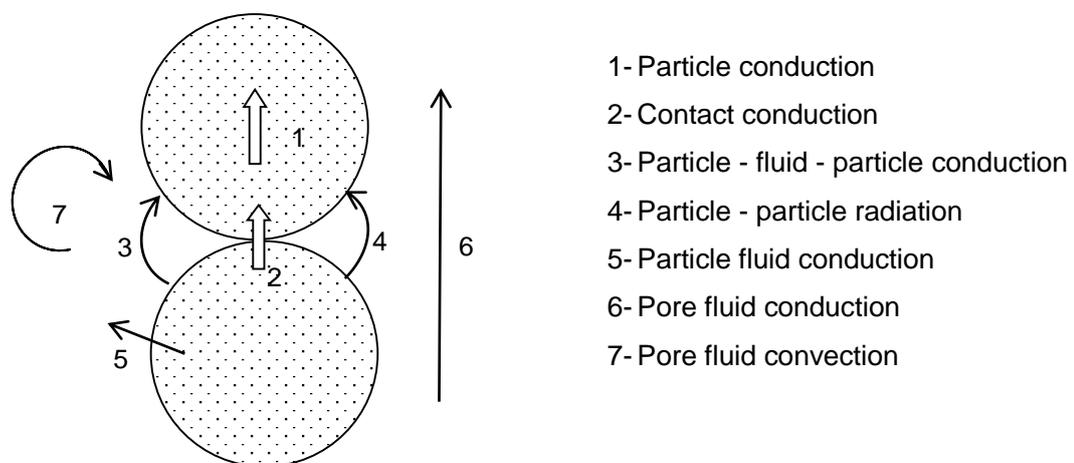


Figure 1-2 : Heat transfer paths in mass materials

The heat flow through any soil mass is directly influenced by the relative proportions of its constituents and the structure of the soil matrix. The variation of physical and thermal properties of the soil constituents make correct description of the heat transfer through soils very complicated. Heat flow through soils is almost entirely by conduction. When a temperature gradient exists in a soil mass heat energy transfers from the hot region to cold region by different means of heat transfer through all soil constituents (soil solids, water and the pore gases). Fourier's law of heat conduction can be used to express this phenomenon. It is an empirical law based on observation and states that the rate of the heat flow in solids and porous materials is directly proportional to the cross-sectional area and to the temperature gradient in the direction of the heat flow.

On the other hand, Heat transfer by convection in soils can be classified according to the nature of the flow. Free or natural convection is induced by the movement of air or water molecular within the soil mass that arises from density differences caused by temperature variations. The free convection can take place only in coarse soil where large pore space allows free movement of fluid particles from hotter regions to cooler regions. On the other hand, forced convection occurs when the water is forced to pass through the soil or rock pores due to pressure difference (hydraulic gradient). Ground water flow is an example of the forced convection in the field soils or rocks. Convection may cause a substantial increase (up to 20%) in the effective thermal conductivity of the soil mass (Farouki, 1986).

Heat transfer by radiation in soils is usually neglected at normal atmospheric temperature. Its effect could reach 10% of total heat transfer when the particle size is over 20mm (Farouki, 1986). Therefore heat transfer by radiation can be significant only for dry coarse crushed stone material. The mechanism of the heat radiation can be explained due to electromagnetic radiation which is propagated as a result of a temperature difference. Thermodynamics theory shows that an ideal radiator will emit energy at a rate proportional to the fourth power of the absolute temperature of the body and directly proportional to its surface area (Holman, 1997).

1.6 Thermal conductivity of soils

Three key properties of soils are thermal conductivity, heat capacity and thermal diffusivity. The thermal conductivity is the most important thermal property while volumetric heat capacity or specific heat capacity can be determined to a reasonable accuracy based on the fractions of the soil constitutions. It is important to mention that the symbol k used in this thesis is referring to the effective thermal conductivity which incorporates all forms of heat transfer that may occur in the soil bulk. This is especially useful when dealing with porous material where different volumetric constituents of different materials are exist and different modes of heat transfer occur. On the other hand, the thermal conductivity of soil constitutes or any other materials will have the same symbol (k) with the relevant subscript. This indicates the true or molecular thermal

conductivity which mainly concerned with conduction. For example, the thermal conductivity of the water will be symbolised as k_w .

Soils are either two or three phase materials that consist of mineral particles, organic matter, and pores which may contain water or air or both. The thermal conductivity of the soil essential depends on the thermal properties of the soil mass constituents. Quartz has relatively high thermal conductivity and air has low thermal conductivity. In static condition (no hydraulic gradient), the thermal conductivity of the soil is less than the highest value of molecular thermal conductivity of its constituents. The thermal conductivity of soils has been found to be a function of several parameters such as: dry density, water content, mineralogy, temperature, particle size, particle shape and volumetric proportions of the soil constituents (Nusier and Abu-Hamdeh, 2003). The amount of the heat transfer is related to the quality of the interparticle contacts and the number of these contacts per unit volume. The presence of liquids or cementing agents at contacts enhances conduction and increase the thermal conductivity of the soil mass. Porosity is the most important macro scale parameter on the thermal conductivity of dry soils: the thermal conductivity of the dry soil increases as the porosity decreases. Low porosity implies high interparticle coordination at the particle scale. Round particles and well-graded soils tend to attain denser packing, higher number of contacts per unit volume and higher thermal conductivity than angular particles (Yun and Santamarina, 2008).

1.7 Steady state Laboratory measurements

The estimation of the thermal conductivity of soils using laboratory methods based on the steady state condition (steady flux methods) can be classified into absolute and comparative methods. The former includes the guarded hot plate method, unguarded hot plate method and heat flow meter technique in which the determination of the power through the specimen is directly calculated by the input power measurements. The latter comprises guarded comparative longitudinal heat flow technique which uses a reference material of known thermal conductivity in series with the specimen. Another classification based on the direction of heat flux can be applied. This classification involves two groups. The first is the steady state longitudinal heat flow method which includes the hot

plate methods, heat flow meter apparatus and the comparative method. The second is the steady state radial heat flow method which comprises the cylindrical and spherical concentric methods. All the steady state methods used to measure the thermal conductivity are based on the application of Fourier's law with one directional heat flow. No standard test has been identified for measuring thermal conductivity of soils using steady state methods. Several configurations of apparatus are available. However, they are mainly designed to measure the thermal conductivity of the insulation materials. The theories behind these methods are used to produce several arrangements of different apparatus that has been used to determine thermal properties of soils. The level of the precision of these configurations depends on how well the designer can control the parameters used in the thermal calculations of these methods. The main concern about these configurations is the challenge of establishing one-dimensional heat flow condition due to the effect of ambient temperature interference (ATI). Pintado (2006) stated that the analyses of the heat transfer for cylindrical systems performed with finite element code estimates the lateral loss can reach 60% of the total heat power input. One target of this research is to design a cylindrical thermal cell that allows to establish one-dimensional longitudinal heat flow by minimizing the lateral loss caused by the ATI.

1.8 Unsteady state laboratory measurements

The unsteady state method (transient Method) measures the thermal conductivity during the transient state. Two common methods are used. The first is the single needle probe method and the second is the dual needle probe method. Both are based on the line-heat source theory derived from a general model of transient heat conduction in a semi-infinite, homogeneous and isotropic material of uniform temperature. The rate of rise in the temperature of the probe depends on the thermal conductivity of the surrounding medium. The relation between the temperature and the logarithm of the time is used to estimate the thermal conductivity of the testing material. Probe methods are more versatile than the steady state methods because they are easy to perform and require short measuring time. On the other hand, they are considered less accurate than steady state method (Mohsenin, 1980). Error may accumulate due to many

factors such as the contact resistance between the probe and the surrounding, size of the probe, heating time, input heat power, position of the sensors in the body of the probe and the type of the probe material. The dual probe has an advantage of measuring thermal diffusivity and heat capacity in addition to the thermal conductivity whereas the single probe can only measure the thermal conductivity.

1.9 Thesis aim and objectives

This thesis is concerned with an experimental investigation for determining the thermal conductivity of soils using steady state methods. The overall aim of this work is to establish an adequate and an accurate experimental procedure for measuring the effective thermal conductivity of soils and borehole thermal grouts to achieve optimal design of ground source heat systems. Also, this work aims to investigate the effect of some physical properties of sandy soils on the measured thermal conductivity.

Objectives

The aim of this PhD project is achieved through the following objectives:

- To investigate the latest developments in designing experimental equipment used to determine thermal conductivity of the soils.
- To develop and construct a new thermal cell that allows measurement of thermal conductivity of wide range of soils with different characteristics.
- To design a new thermal grout that comprises some otherwise unwanted materials and to use the new thermal device to measure the thermal conductivity of such grout.
- To generate a quantitative experimental data for previously untested sandy soils to investigate the relations between the thermal conductivity and physical properties of such soil.

Three main stages are designed for this project.

1. Develop, design and build a new cell to determine the thermal conductivity of the soils based on one-dimensional steady state heat flow and carry out tests using typical laboratory prepared samples to evaluate the performance of the new cell.

2. Design and test new thermal grout comprises low cost industrial and domestic materials (PFA and ground glass) for borehole heat exchangers.
3. Undertake a comprehensive series of experimental tests to measure the thermal conductivity of new type of soil (Tripoli sand) that has not been thermally tested at different conditions.

1.10 Scope of the thesis

This research is a part of study related to the use of the ground as a source and storage of thermal energy. As mentioned in the previous section, the present work consists of three main parts. Each part has different topics. However the three parts are linked together as they are related to the design and the performance of the thermogeology heat exchanger systems.

Consequently, the thesis is divided into three main chapters. Each chapter has its own methodology, experimental work, results and discussions. However, the literature review related to all topics covered in the three chapters is congregated in one chapter. Therefore, the thesis configuration will be as following:

1.10.1 Chapter one (introduction)

In this chapter the general background of thermogeology heat systems and the development of this technology as a new source of clean energy are illustrated, identifying the importance of the thermal properties of soils and grouting materials on the efficiency of the thermogeology systems.

1.10.2 Chapter two (literature review)

This chapter presents an overview of topics related to thermal properties and thermal measurements of soils. Firstly, the general basic principles associated with heat transfer including forms of heat flow are summarized. The basic information of thermal properties of soils including factors that influence heat transfer in soil is then explained. Also, this chapter presents the methods used to measure the thermal conductivity of soils. These methods include field, laboratory and prediction methods. More focus is applied on the steady state laboratory techniques as it is the main area of this research work. Finally, the types of thermal grouts used as filling materials and the enhancement of the thermal

conductivity of such grouts in conjunction with the experimental tests required for thermal grouts are illustrated. Each topic in this chapter is supported with some of the associated historical and latest work done.

1.10.3 Chapter three (Steady-state thermal conductivity new apparatus)

This chapter outlines a sequence of stages to develop a new robust device to measure the thermal conductivity of soils. The first part of this chapter begins with the design criteria and the theory behind the proposed thermal cell. The main factors that influence the design and should be taken into consideration with discussion of the design options are illustrated. The description of the final configuration and the details of each part of the apparatus are then presented. The second part of this chapter presents the experimental procedures that should be followed in the determination of the thermal conductivity of soil samples under different conditions. The third part involves the experimental tests required to evaluate the performance of the thermal cell. These tests investigate the effect of the boundary conditions on the measured thermal conductivity such as effect of the thermal jacket, effect of sink discs and effect of thermocouples. Also, these tests involve comparison between the new apparatus results and transient probe method results. Finally, discussions and interpretations of the experimental results are presented.

1.10.4 Chapter four (Thermal enhancement of pulverized fuel ash (PFA)-based grout)

This chapter is related to the design and testing of a new thermal grout that comprised unwanted materials (PFA and ground glass). In the introduction of this chapter, a general view of the importance of the grout in the thermogeology systems and the necessity to improve its thermal properties are illustrated. The materials that are used as base or enhancing material are then clearly defined. Following this, the mix design and sample preparation are described. The experimental testing including grout flow, shrinkage, thermal conductivity and permeability is then explained. In the discussion section, the results obtained from the experimental part are categorized according to their thermal conductivity results and graphically presented. This section also includes comparison and

evaluation of all mix types to select the best design that can be used effectively as thermal grout for borehole heat exchangers.

1.10.5 Chapter five (Thermal conductivity of Tripoli sand)

This chapter can be considered as a case study concerning the experimental thermal conductivity measurements of sandy soil, which has not been previously thermally tested (Tripoli Sand). The physical properties of Tripoli sand including the description, sieve analysis and mineralogical composition are presented. The methodology section includes the samples preparation and the details of the thermal conductivity experimental procedure. The results of the experimental work are then tabulated. A selection of common existing predictive models used to predict the thermal conductivity of soils are validated against experimental results and graphically plotted. The next section includes discussion of the results obtained from the experimental work in which the effect of dry density and degree of saturation on the thermal conductivity of such soil explained in details. Also, comparison between experimental results and results obtained from the predictive models are included in this section. Finally, an empirical model to predict the thermal conductivity of such soils based on the experimental results is obtained and validated.

1.10.6 Chapter six (conclusions and recommendations)

Bullet points summarising the conclusions drawn from the three subjects covered in this research along with suggestions for future research topics related to this work are presented in this chapter.

Chapter 2 : Literature review

2.1 Introduction

This chapter addresses the general scientific principles related to heat transfer and basic information of the thermal properties of soils. The factors that influence flow and the storage of the heat in the soil are clarified. It also explains the main methods used for measuring the thermal conductivity of soils, focusing on the steady state laboratory techniques. The impact of the thermal resistance of the borehole and the effect of the thermal properties of the grout on the efficiency of a borehole heat exchanger is finally highlighted. For each topic, some related previous works are illustrated.

2.2 Thermal energy, heat and temperature

2.2.1 Thermal energy

Energy is one of the most fundamental and universal concepts of physical science. The basic unit of energy is the joule. $1\text{J} = 1\text{ N}\cdot\text{m} = 1\text{ kg m}^2\text{ s}^{-2}$. Thermal energy is a term used to describe the sum of the sensible and latent internal energy components (Bals and Gengel, 2008). Sensible energy is the internal energy that associated with kinetic energy of atoms and molecules within the system where latent energy is related with the binding forces between the molecules.

2.2.2 Heat

Heat is measured in energy units. It refers to processes by which energy is transferred. When a warmer body is brought into contact with a cooler body, heat flows from the warmer one to the cooler until their two temperatures are identical. The warmer body loses a quantity of thermal energy ΔE , and the cooler body acquires the same amount of thermal energy. This process can be described by saying that ΔE joules of heat has passed from the warmer body to the cooler one.

Therefore, the heat is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of temperature difference (Bals and Gengel, 2008).

2.2.3 Temperature

Temperature can be defined in several ways. A convenient operational definition of temperature is that it is a measure of the average translational kinetic energy associated with the disordered microscopic motion of atoms and molecules. Therefore, at higher temperatures, the molecules possess higher kinetic energies, and as a result the system has a higher internal energy. In other words, temperature can be expressed as the "intensity" with which the thermal energy in a body manifests itself in terms of chaotic, microscopic molecular motion. It is important to notice that the major form of thermal energy is due to the random movement of the molecules. However, molecules can also undergo other kinds of motion, namely rotations and internal vibrations. These latter two forms of thermal energy do not contribute to the temperature. This can explain why two objects with the same internal energy do not necessarily have the same temperature.

2.3 Forms of heat transfer

Heat is energy passing from one object or material to another because of a difference in temperatures. Heat transfer in soils is quite complex and can be in any of three forms: conduction, convection and radiation.

2.3.1 Conduction

Heat conduction is the flow of internal thermal energy from a region of higher temperature to one of lower temperature by the interaction of the adjacent particles (atoms, molecules, ions, electrons, etc.). When the fast molecules bang into the slow molecules, the faster molecules slow down and the slower molecules speed up. The hot surface has cooled down and the cold surface has heated up. When temperatures are equal, conduction is balanced which means no more heat flows.

Fourier made very significant contributions to the analytical treatment of conductive heat transfer and summarized them in Fourier's law of heat conduction. It states that the rate of heat flow (dQ/dt) through solid or porous materials is directly proportional to the area of the section (A) and to the temperature gradient in the direction of the heat flow (dT/dL). In other words, heat transfer rate per unit area is proportional to the temperature gradient (Holman, 1997). As illustrated in Figure 2-1, the heat transfer rate can be expressed by:

$$\frac{q}{A} \propto \frac{dT}{dx} \quad 2.1$$

Using a proportionality constant,

$$q = -kA \frac{dT}{dx} \quad 2.2$$

where, q is the rate of heat transfer (dQ/dt), A is the cross-sectional area perpendicular to the direction of the heat flow and $\frac{dT}{dx}$ is the temperature gradient.

The proportionality constant k is called the thermal conductivity of the material and measured in $W/m.K$. The minus sign ensures that heat flows down the temperature gradient.

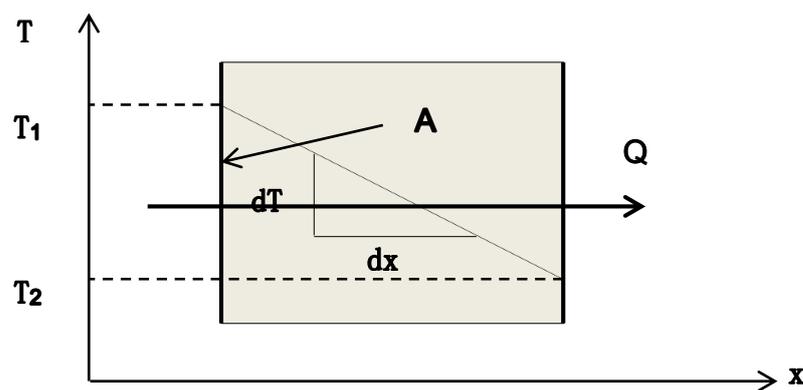


Figure 2-1 : Unidirectional conduction heat transfer

In soils, heat is transferred mainly by conduction (Farouki, 1986). However, other mechanisms may contribute in some measure of heat transfer. Conduction in soil is the transmission of thermal energy from particle to particle or through pore

fluids, i.e. conduction occurs in all constituents of the soil mass (solids, liquid and gas). The rate of heat-transfer in soils are highly dependent on the thermal properties and on the mass fraction of the soil constituents as well as on the temperature gradient.

2.3.2 Convection

Convection is the transfer of internal energy into or out of an object by the physical movement of a surrounding fluid that transfers the internal energy along with its mass. Although the heat is initially transferred between the object and the fluid by conduction, the bulk transfer of energy comes from the motion of the fluid. Convection can arise spontaneously (or naturally or freely) through the creation of convection cells or can be forced by propelling the fluid across the object or by the object through the fluid. Convection can also exist in processes that involve change of phase of fluid (latent heat) due to the fluid motion induced during the process such as the rise of the vapour bubbles during boiling or the fall of the liquid drops during condensation (Bals and Gengel, 2008).

Sir Isaac Newton, in 1701, described the basic rate equation for convective heat transfer by which is known as Newton's Law of Cooling, expressed as:

$$q = hA(T - T_{\infty}) \quad 2.3$$

where q is the rate of convective heat transfer in W , A is the area normal to the direction of heat flow in m^2 , T is the surface temperature in K , T_{∞} is the surrounding temperature in K and h is the convective heat-transfer coefficient in $(W/m^2.K)$.

Convection occurs in saturated and partially saturated soils. It becomes increasingly important as the pore size increases and is significant in granular soils. Also, convection becomes essential in granular soils in which permeability is great enough to allow ground water to flow at sufficient rate. In this case convection becomes significant and the permeability will be a key parameter of heat transfer. Free or natural convection is induced by the buoyancy forces that arise from density differences caused by temperature variations practically in course dry soil. On the other hand, forced convection occurs when the water or air is forced to pass through the soil or rock pores due to pressure difference.

Ground water flow is an example of the forced convection in the field soils or rocks. Convection may cause a substantial increase (up to 20%) in the apparent thermal conductivity of the soil mass (Farouki, 1986).

2.3.3 Radiation

Radiation is the transfer of heat energy by electromagnetic wave motion that arises due to the temperature of the body. The waves travel through space and get absorbed by other atoms. The amount of energy absorbed by an object depends upon the object's absorptivity and the intensity of the radiation striking the object. Thermodynamic considerations show that an ideal radiator will emit energy at a rate proportional to the fourth power of the absolute temperature of the body and directly proportional to its surface area (Welty 1978). Thus:

$$q_{emitted} = \sigma \cdot A \cdot T^4 \quad 2.4$$

where q is the heat transfer rate in watts, σ is the Stefan-Boltzmann constant 5.699×10^{-8} in $W/m^2 K^4$, A is the surface area in m^2 and T is the temperature.

In soils, radiation usually makes a negligible contribution to heat transfer at normal atmospheric temperature. The total contribution of radiation to the heat transfer process is estimated to be less than 1% (Rees et al., 2000). Its effect could reach 10% of total heat transfer when the particle size is over 20mm (Farouki, 1986). Therefore heat transfer by radiation can be significant only for dry coarse crushed stone material.

2.4 Thermal properties of soils

Studies conducted in the past reveal that heat transfer through a soil mass depends on its thermal properties and hence estimation of soil thermal properties is essential. These properties comprise thermal conductivity k , specific heat capacity C_p and thermal diffusivity α . The three parameters are related by:

$$\alpha = \frac{k}{\rho C_p} \quad 2.5$$

Thus, with the knowledge of any two of the thermal properties, in conjunction with the material density, the third property can be determined. The thermal conductivity is the most important thermal property. While volumetric heat

capacity or specific heat capacity can be determined to a reasonable accuracy based on the fractions of the soil constitutions, the thermal conductivity is difficult to determine accurately.

2.4.1 Thermal conductivity of soils

Thermal conductivity is defined as the amount of heat transferred through a unit area in unit time and under the effect of a unit temperature gradient (Hillel, 1980) and has *SI* units of $W/m.K$. Thermal conductivity is related to heat conduction in most of the heat transfer fields. Soils are either two or three phase materials that consists of mineral particles, organic matter, and pores which may contain water or air or both. The molecular thermal conductivity of solids is higher than those of water and air and the thermal characteristics of each component can be widely differing. The thermal conductivity of soils has been found to be a function of several parameters such as: dry density, water content, mineralogy, temperature, particle size, particle shape and volumetric proportions of the soil constituents (Nusier and Abu-Hamdeh, 2003). Therefore, the thermal conductivity of the soil is highly connected with its physical characteristics, which means any change in soil state leads to a change in its thermal conductivity. Due to the complexity of the soils nature, all measurement methods for soil thermal conductivity have their own difficulties and complexities. For example, the main component of the soil that is affected by temperature change is water and the thermal conductivity of the soil is highly dependent on the moisture content but the water content can also change as the temperature changes.

A wide collection of research has been established in studying the thermal conductivity and other thermal properties of soils. This research is related to the investigation of the thermal conductivity measurements of soils either in a field or in the laboratory as well as prediction methods. Farouki (1986) provided a comprehensive review of the literature related to thermal conductivity of soils.

2.4.2 Heat capacity of soils

Soil heat capacity measures the amount of thermal energy it takes to raise the temperature of the soil by one degree (Banks, 2008). This property is expressed as volumetric heat capacity when it related to volume (C_v) and defined as the

amount of heat required to rise the temperature of unit bulk volume by one degree. In contrast, it is expressed as specific heat (C_p) when it related to mass. The *SI* units of the specific heat capacity are $J.kg^{-1}.K^{-1}$. The heat capacity of the soil varies depending on the amount of moisture and the soil composition. Soil solids have heat capacity less than that of water. Consequently, wet soils have higher heat capacities than dry soils and as a result a wetted soil takes longer to heat in comparison with a dry soil. This is due to the fact that the amount of energy required to increase the temperature of water ($C_v = 4180 J.K^{-1}.m^{-1}$) by $1^\circ C$ is much greater than that required to warm soil solids by $1^\circ C$. The high specific heat capacity of soil permits a large exchange of energy to take place without greatly modifying the soil temperature. Abu-Hamdeh (2003) found that the specific heat of the soils increases with increasing of its water content at given bulk density. He also showed that the volumetric heat capacity of the soil computed by theoretical relations agreed closely with that measured by calorimetric method.

In a soil mass, if M_s , M_w and M_a represent the mass fraction and C_s , C_w and C_a the specific heat capacities of solids, water, and air respectively with total mass of M , the specific heat of this soil mass (C_p) can be calculated as:

$$C_p = \frac{1}{M} (C_s.M_s + C_w.M_w + C_a.M_a) \quad 2.6$$

Because of the small mass of the air compared with the mass of the water and solids, the third term in the right hand side of the equation can be neglected and the equation can be written as:

$$C_p = \frac{1}{M} (C_s.M_s + C_w.M_w) \quad 2.7$$

Experimentally, the specific heat can be measured by mixing water and soil solids of different temperatures and leaving them to balance in temperature. Commonly a soil temperature T_s of $0^\circ C$ and a water temperature of T_w $20^\circ C$ are used and the mixture temperature T_{mix} is measured. The energy balance of the water-soil mixture can be written as:

$$(C_s.T_s.M_s) + (C_w.T_w.M_w) = (C_s.M_s + C_w.M_w)T_{mix} \quad 2.8$$

where M_s and M_w are the masses of soil and water in (kg) and C_s and C_w are the specific heats of soil and water in (J/kgK).

2.4.3 Thermal diffusivity of soils

Thermal diffusivity (α) is defined as the ability of a substance to transmit a difference in temperature. In other words, it is a measure of the propagation rate of the heat transfer. Thermal diffusivity is expressed as thermal conductivity divided by the product of the specific heat and density and has units of (m^2s^{-1}).

$$\alpha = \frac{k}{\rho C_p} \quad 2.9$$

This means that soils with high thermal diffusivity rapidly adjust their temperature when subjected to temperature gradients, because they conduct heat quickly in comparison to their ability to store heat.

2.5 Factors influencing thermal properties of soils

The flow and storage of the heat in the soil are mainly influenced by its thermal properties, which comprise the thermal conductivity, thermal diffusivity and volumetric heat capacity. These properties depend on several factors which can be classified into two broad groups: those which are inherent to the soil itself such as soil texture, mineralogical composition and grain size distribution, and those which can be managed externally including water content, temperature and soil bulk density (Abu-Hamdeh et al., 2001). The most important property is the thermal conductivity. This has a significant effect on controlling the heat transfer through the soil (Nusier and Abu-Hamdeh, 2003). Soil is composed of mineral particles, organic matter, and pores which may contain either water or air. The transmission of the heat through the soil is dependent on the physical properties of its constituents.

2.5.1 Influence of moisture content

The relationship between water content and thermal conductivity in soils has been widely investigated (Penner et al., 1975; Farouki, 1986; Singh and Devid, 2000; Tarnawski et al., 2000b; Krishnaiah and Singh, 2003; Nusier and Abu-Hamdeh, 2003; Sakaguchi et al., 2007; Hall and Allinson, 2009b; Hamuda, 2009).

These investigations have conclusively been shown that the thermal conductivity of the soil increases with increasing water content.

Soils are either two or three phase materials. In dry conditions, as the thermal conductivity of the air is much lower than those of the other components, heat transfers only through contact points between the soil particles. As the water content increases and starts to fill the pore spaces, more water begins to collect around the contact points and started to form water bridges between soil grains (Hall and Allinson, 2009b). The water bridges improve the heat transfer from one grain to another. Since the water has significantly higher thermal conductivity than air (0.6 W/m.K for water vs. 0.025 W/m.K for air), the bulk thermal conductivity of the soil is directly linked with increasing its water content. The thermal conductivity at first increases rapidly as the moisture content increases, but beyond a certain moisture content, the rate of increase becomes much less (Singh and Devid, 2000).

Based on numerous experimental tests, Kersten (1949) proposed empirical relations based on the fact that the thermal conductivity is linearly related to the logarithm of the water content at constant dry density. He obtained two empirical equations for predicting the thermal conductivity of soils by knowing its water content and dry density. The first equation is for unfrozen silt and clay soils containing 50% or more silt and clay (eq. 2.10) and the second is for unfrozen sandy soils (eq. 2.11).

$$k = 0.1442 \cdot (0.9 \log w - 0.2) 10^{0.6243 \rho_d} \quad \text{For} \quad w \geq 7\% \quad 2.10$$

$$k = 0.1442 \cdot (0.7 \log w - 0.4) 10^{0.6243 \rho_d} \quad \text{For} \quad w \geq 1\% \quad 2.11$$

where ρ_d is the dry density in g/cm^3 .

Johansen (1975) considered the relation between the effective thermal conductivity and the water content as being a linear relationship. He introduced the concept of the Kersten number k_e , which depends on the degree of saturation, to calculate the thermal conductivity of a soil in a partially saturated state. The thermal conductivity of the soil, according to Johansen's equation (2.12), in

partially saturated state, can be estimated by linear interpolation between dry and saturated thermal conductivities.

$$k = (k_{sat} - k_{dry}) \cdot k_e + k_{dry} \quad 2.12$$

The thermal gradient caused by the temperature differences causes moisture to migrate from hot to cold places. This phenomenon occurs in partially saturated soils and involves the interaction of several physical mechanisms. The moisture movement, which occurs in both liquid and vapour phases, gives rise to a transfer of thermal heat and results in redistribution of temperature. Thomas and Sansom (1995) made a fully coupled analysis of heat, moisture and air in partially saturated soil and highlighted the importance of the inclusion of the air phase in the thermal conductivity of soils.

2.5.2 Influence of dry density

It has long been recognized that an increase in the dry density of soil results in an increase in its thermal conductivity (Smith, 1942). This can be explained by the fact that any change in the density of soils leads to change in the void ratio and porosity. In other words, an increase in the soil density at constant water content leads to replacement of the air volume in pore spaces by higher thermal conductivity minerals as a result increasing the overall thermal conductivity. With an increase in the soil's dry density (reducing the porosity), more soil particles are packed into a unit volume and, thus, the number of contact points between the solid particles increases which provides more heat flow paths resulting in higher thermal conductivity.

The relationship between the thermal conductivity of soils and their densities has been widely investigated. For example, Kersten (1949) found that the relation between the logarithm of the thermal conductivity and the dry density at constant water content can be expressed linearly. The slope of the linear relation for a given soil is also approximately the same at different water contents. Based on several tests, he expressed this behaviour by the following equation:

$$k = A \cdot (10)^{B \cdot \gamma_d} \quad 2.13$$

where A and B are empirical parameters depend on the soil type.

Singh and Devid (2000) proposed several empirical equations for the estimation of thermal resistivity of soils (resistivity is the reciprocal of conductivity) at dry and moist conditions. They observed that the absolute difference between the thermal conductivity values obtained from the proposed equations and the experimental results (using the transient needle method) was less than 15-20%. They also noticed that the predicted and experimental results were very close when the test is conducted dry soils. Nusier and Abu-Hamdeh (2003) investigated the thermal conductivity of two soils as a function of the bulk density using transient methods. The soils were classified as sand and loam. They conclude that the thermal conductivity increased with increasing bulk density for the two soils. Yun and Santamarina (2008) highlighted the effect of the quality of interparticle contacts between the solid grains and the number of contacts in the unit volume on the thermal conductivity in granular materials.

Several graphs describing the relationship between the thermal conductivity and the dry density of soils are available in the literature e.g. (Smith, 1942; Farouki, 1986; Krishnaiah and Singh, 2003; Chen, 2008). However, the values shown in these graphs express the thermal conductivity of particular type of soils and cannot be used as standard values. This is because although the thermal conductivity of the soil is highly influenced by the density, other factors should be taken into consideration in measuring or predicting the thermal conductivity of soils.

2.5.3 Influence of soil constituents

Soil consists of solid particles surrounded by pore spaces filled with water or air or both. The thermal conductivity of the soil is essentially dependent on the thermal properties of the soil mass constituents and the volume fraction of each constituent. For example, sands with high quartz content generally have a greater thermal conductivity than sands with high contents of plagioclase feldspar and pyroxene (Kersten, 1949). The thermal conductivity of some important soil components are given in Table 2-1.

Soil particles are composed of one or more minerals such as quartz or clay minerals or organic material. Quartz has the highest thermal conductivity and air the lowest. The different in the mineralogical composition between sand and clay

soils is likely to be the primary reason that sandy soils display higher thermal conductivity than clay soils. The presence of liquids or cementing agents enhances the conduction and increases the thermal conductivity of the soil mass. The effect of the soil composition can be observed when the saturated soil is exposed to freezing temperature. At the freezing point the soil thermal conductivity can change dramatically due to the changes of the primary mode of heat transfer from convection in liquid to conduction in ice (Kersten, 1949).

Material	Thermal conductivity ($W/m.K$)	References
Quartz	7.69	Horai (1971)
Kaolinite	2.64	Brigaud and Vasseur (1989)
Illite	1.85	Brigaud and Vasseur (1989)
Water	0.6096	Ramires et al. (1995)
Ice	2.22 @ 0 °C	Engineering toolbox (2008)
Air	0.02619	Stephan and Laesecke (1985)

Table 2-1 : Thermal conductivity for some of soil constituents

2.5.4 Influence of soil structure or texture

Soil texture is another factor that can influence the soil's thermal conductivity. The soil structure is important because it describes the arrangement of the solid primary and secondary particles with respect of each other, and the orientation with respect to the direction of the heat flow. The thermal conductivity of coarse textured, angular grained soils is higher than that of fine textured soils. Also, uniformly graded soils exhibited lower thermal conductivity than well graded soils. This is because in the well graded soils, the space between the large grains gets occupied by the smaller grains and hence conductivity increases. The particle shape and the presence of bonding agents will influence the degree of contact resistance and the continuity of the solid phase, which in turn influence its thermal conductivity. The number and nature of the contacts between the soil particles also affects the thermal conductivity. This is because most of the heat transfers through these contact points or areas, especially in case of dry or nearly dry soils

(Farouki, 1986). The number of these contacts is directly linked with the shape of the soil particles and the degree of compaction. In clay soils, the particles are flat plate shaped and they carry negative charge in flat surface and positive charge around the edges and corners. Therefore, attraction or repulsion forces are developed according to the positive or negative surface charges are in contact (see Figure 2-2). The direction of the flat plates (parallel or perpendicular) and the existence of water controls the thermal conductivity of clay soils.

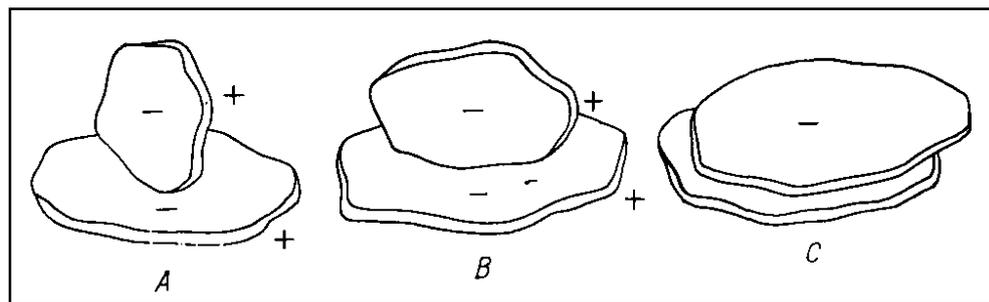


Figure 2-2 : Types of bond between plate-like clay particles

The compaction and the presence of absorbed water molecules can influence these forces. Studies of the effect of soil matrix structure on thermal conductivity and heat flow in two phase geomaterials have shown that the thermal conductivity is higher in cemented material than in loose particle packs (Johansen, 1975). Furthermore, theoretical investigations showed that the thermal conductivity of particle packs decreases with increasing sphericity of particles (Côté and Konrad, 2005).

In sands, the bonds between the solids can be improved by clay or other binder. This significantly improves the thermal conductivity due to the improvement of the contact between the particles. Farouki (1986) found that in spite of the much lower thermal conductivity of the kaolinite as compared with quartz, the thermal conductivity of cohesion-less granular material can be significantly increased by adding a small amount of clay.

2.5.5 Influence of particle size

The density and the porosity of any soil are connected with the grain size distribution. Therefore, the thermal conductivity is directly affected by this

property. The number of contacts between the soil particles is linked with the grain size distribution of the soil mass. Many researchers have recognized the importance of the heat transfer at the contacts between soil particles eg. (Smith, 1942; Farouki, 1986; Tarnawski et al., 2002; Krishnaiah and Singh, 2003). They conclude that in dry or nearly dry soils, the contact conduction is considered to be the major factor limiting overall conduction. However, in all types and conditions of soils the interfacial effects between the soil constituents (solid, liquid and air) maintain their importance to heat transfer (Farouki, 1986). Particle size also affects the thickness of water films surrounding soil particles. The amount of water required to produce films of a given thickness depends on the specific surface area (the surface area per unit weight or volume) of the particles which is a function of particle size and shape. Clay particles have much higher specific surface area than sands and therefore require more water to produce a film of a given thickness (Sepaskhah and Boersma, 1979).

Research has also showed that thermal conductivity of soils increases as the grain size increases. Tavman (1996) explained this property due to the fact that as the grain size decreases, more particles are necessary to reach the same porosity consequently more thermal resistance between particles arises. Nusier and Abu-Hamdeh (2003) came up with same conclusion when they found sandy soils had higher thermal conductivity values than loam soils at all bulk densities.

2.5.6 Influence of temperature

The thermal conductivity of the soils can be affected by temperature, because each of the constituents has different temperature-dependent thermal properties. Most crystalline minerals in soils show a decrease in thermal conductivity with increasing temperature when tested as a solid phase material (Brandon and Mitchell, 1989). It is considered that the heat transfers through crystalline minerals by both compressive and longitudinal waves which become less harmonic with increasing temperature. In contrast, the thermal conductivity of water and gases increases with increasing temperature (Van Rooyen and Winterkorn, 1957). Both liquids and gases transfer heat by collisions between molecules. Therefore, any increase in molecular collisions caused by temperature rise leads to increasing thermal conductivity.

Much research has been made on the temperature dependence of the thermal conductivity of soils eg (Andersland and Anderson, 1978; Sepaskhah and Boersma, 1979; Brandon and Mitchell, 1989; Tarnawski et al., 2002; Sakaguchi et al., 2007; Hamuda, 2009). They showed that the thermal conductivity of soils increases as temperature increases. It is also observed that this increase is highly dependent on the water content of the soil. Brandon and Mitchell (1989) stated that there was an indication that the thermal conductivity of dry sand decreases slightly with temperature. This phenomena was also observed when the thermal conductivity of Toyoura sand was tested in nearly dry state (Momose and Kasubuchi, 2002). Generally, the temperature dependency of thermal conductivity of soils at temperature above 0°C can be ignored without substantial error in majority of engineering applications (Andersland and Anderson, 1978). Hamuda (2009) also came up with same conclusion when he found that the increase of the average temperature of saturated sand specimen from 25.49 °C to 38.92 °C increases the thermal conductivity by 1.6%.

2.6 Field thermal conductivity measurements

An important development to measure the thermal properties of the underground in situ is the thermal response test (TRT). This test was first developed in Sweden and USA in 1995 and now is used in many countries word wide (Austin, 1998). The thermal response test is an effective method to determine the ground thermal properties. A known thermal load is injected into a borehole heat exchanger and accurate measurements of the inlet and outlet temperatures of the circulating fluid are recorded. In general, the TRT provides only an average thermal conductivity value along the borehole heat exchanger, and typically takes 50 hours to perform. The analysis of the thermal response test data is based on Kelvin’s line-source theory. The approach adopts the analytical solution for the response to an infinite constant-strength line source within a homogeneous, isotropic, infinite medium. At constant lateral heat flow, the temperature field around the borehole is only depends on time t and radial distance from the borehole r . According Garslaw and Jaeger (1959), the temperature field can be given by:

$$T_{(r,t)} = T_i + \frac{Q/H}{4\pi k} \int_{\frac{r^2}{4\alpha t}}^{\infty} \frac{e^{-u}}{u} du \cong T_i + \frac{Q/H}{4\pi k} \left[\ln \left(\frac{4\alpha t}{r^2} \right) - \gamma \right] \quad 2.14$$

where T_i is the initial undisturbed ground temperature, $\alpha = k/\rho c$ the thermal diffusivity, Q the constant heat injection, H the length of the borehole and $\gamma = 0.577$ is the Euler's constant.

Introducing a thermal borehole resistance between the fluid and the borehole wall R_b , the average fluid temperature of the circulation fluid T_f , caused by the specific radial heat flow $q = Q/H$ as a function in time can be written as:

$$T_f = \frac{q}{4\pi k} \ln(t) + \left[\left(\frac{q}{4\pi k} \left(\ln \left(\frac{4\alpha t}{r^2} \right) - \gamma \right) - qR_b \right) \right] + T_i \quad 2.15$$

Implementation is by determining the slope of the average fluid temperature development versus the natural log of the time curve:

$$T_f(t) = a \ln(t) + b \quad 2.16$$

where, a is the slope of the curve, and b is the y- intercept of the curve.

Thus, the effective ground thermal conductivity can be determined from the slope a of this linear relation:

$$k = \frac{q}{4\pi a} \quad 2.17$$

The TRT can predict the effective thermal conductivity within an error of $\pm 10\%$ which is accepted for an appropriate prediction for thermogeology heat yield (Witte et al, 2002; Wagner and Clauser, 2005). The TRT has been investigated in many studies. These have been carried out to describe the test procedure, evaluate of the obtained results, for analytical models, numerical models and some case studies in different countries. (AUSTIN, 1998; Signorelli et al., 2007; Marcotte and Pasquier, 2008; Sanner et al., 2008; Esen, 2009; Wang et al., 2009; Al-Khoury et al., 2010; Wang et al., 2010). The main disadvantages of the thermal response test are the high cost and the long time required to perform the test as the time required to reach steady state condition can be relatively long.

2.7 Laboratory thermal conductivity measurements

Methods of measuring thermal conductivity can be classified into steady-state and transient state methods. Each of these methods includes a number of experimental techniques.

2.7.1 Steady state experimental techniques

The steady state methods measure the thermal conductivity when the heat flux through the soil reaches a constant level and the temperature of the soil specimen at any point remains constant with time. Steady state methods involve the production of a temperature difference between the sides of the soil specimen (Farouki, 1986). Only the temperature drop across the specimen and the heat flux are needed to determine the thermal conductivity (Tan et al., 2006). The main weakness of steady state methods is the long time required to reach the steady state condition, which allows moisture migration to take place from hot to cold regions.

The estimation of the thermal conductivity of soils using methods based on the steady state condition (steady flux methods) can be classified into two main categories: The first is the steady state longitudinal heat flow method which includes the hot plate methods, heat flow meter apparatus and the comparative method. The second is the steady state radial heat flow method which comprises the cylindrical and spherical concentric methods. This classification is based on the direction of heat flux. Steady flux techniques also can be classified into absolute and comparative methods. The former includes the guarded hot plate method and heat flow meter technique. In this case determination of the power through the specimen is directly calculated by the input power measurements. The latter comprises a guarded comparative longitudinal heat flow technique which uses a reference material of known thermal conductivity in series with the specimen to be tested (Momose et al., 2008). All these classifications are based on the application of Fourier's law with one-dimensional heat transfer. In all cases, the temperature drop across the specimen and the heat flux through the cross-sectional area are needed to determine the thermal conductivity (Tan et al., 2006).

2.7.1.1 Hot plate methods

Since 1898, the hot plate technique for measuring the thermal conductivity of insulation materials has been in existence in different forms (Salmon, 2001). In these methods, the specimen is sandwiched between two flat hot and cold plates. Due to the temperature difference, a thermal gradient is created through the sample. The heat flux, which is defined as the amount of the input heat power

passing through the cross sectional area of the specimen, can be determined from the power input and the cross sectional area of the specimen. By knowing the temperature drop, the heat flux and the length of the specimen, Fourier's law of unidirectional heat transfer can be applied to calculate the thermal conductivity. From the above definition, it is clear that the determination of the thermal conductivity is entirely reliant on the accurate estimation of the heat flux through the specimen. Various configurations of apparatus for measuring thermal conductivity of soils have been established and the success of each technique depends on the proper design of the apparatus, mainly the degree of control of all boundary conditions.

2.7.1.1.1 The guarded hot plate (GHP)

The guarded hot plate method is generally recognized as the principle absolute method and considered to be the most accurate technique for determining the thermal conductivity of insulation materials. The method is widely used and has been adopted by several organizations as a standard test such as: ASTM C177, ISO 8302, BS 874 and DIN 612 (Salmon, 2001). The principle of the GHP is to generate a known unidirectional heat flux through specimen with infinite width bounded by parallel planes. The heat flux is produced by a heater plate which consists of a central plate (metering area) surrounded by an annular guard heater plate with a small air gap in between. The function of the metering heater is to produce the required heat flux to maintain a desired temperature gradient across the area of the specimen. The purpose of the guarded heater is to reduce the radial heat losses from the metering section by creating a temperature close to that of the metering area. A cold plate which acts as a heat sink is placed on the other face of the specimen with temperature below that of the hot plate. Figure 2-3 shows the principle characteristics of the guarded hot plate apparatus.

Two main configurations of GHP apparatus can be observed: the first in which one specimen is sandwiched between the heater plate and the cold plate, the other in which the heater plates are sandwiched between two specimens and two cold plates are used. In the latter, the flux generated from the central heating plate is divided by two because it is shared equally between the two specimens.

Also, the average of temperature difference of the two specimens is used in the calculations of thermal conductivity.

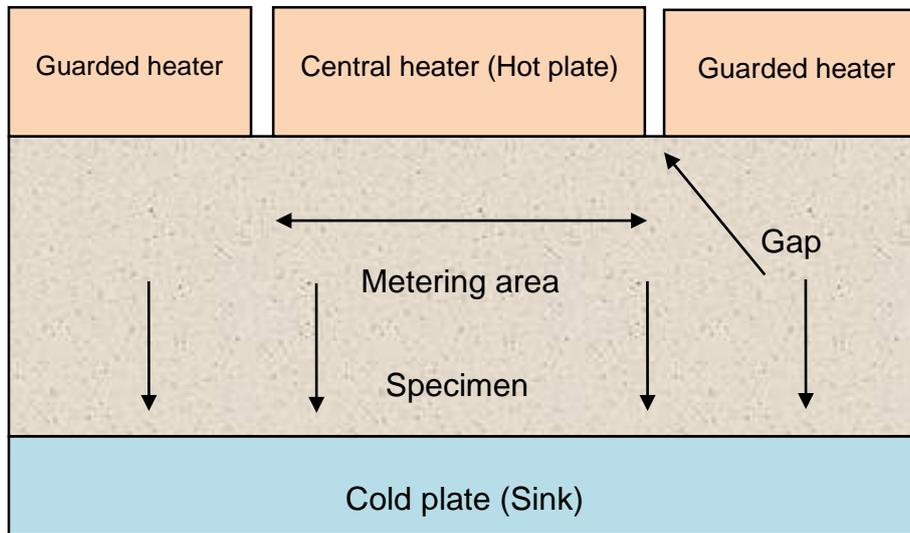


Figure 2-3 : Principle characteristics of GHP apparatus

The effective thermal conductivity (k) can be deduced using the equation developed by Fourier for heat conduction with one dimensional heat flow at steady- state condition:

$$k = \frac{q L}{A \Delta T} \quad 2.18$$

where, q is the rate of heat transfer, ΔT is the temperature drop, L is the specimen thickness, and A is the cross – sectional area.

Recently, more developments have been incorporated in this technique. Although these developments employ the same theory, some important modifications can be noted. These modifications are associated with the size or the scale of the apparatus as thicker insulation has become more common together with improvement of the instrumentation. Also, radial heat losses have been minimized by integrating additional guards. In addition, the effect of computer systems for analysing and acquiring data has been valuable (Salmon, 2001).

Among the absolute methods, the GHP is considered the most accurate and precise technique for determining the thermal conductivity of the insulating materials (XamÄjn et al., 2009). However, the most important disadvantage of

this method is the long time required to reach the steady state especially for material with very low thermal conductivity. Also, heat transfer across the gap via the specimen caused by an incorrect balance condition can be significant especially for material with relatively high thermal conductivity (greater than 0.75 (W/m.K)) (Salmon *et al.*, 2009). In addition, the method is applicable only for large specimens (Clarke *et al.*, 2008).

2.7.1.1.2 Unguarded hot plate method

British Standard BS 874 -2-2 (1988) describes this method for determination of thermal conductivity of insulating homogenous solid materials. The method is considered as not absolute because a reference material of known thermal conductivity is required for calibration of the apparatus. The construction of the plates should have the same dimensions as the guarded hot plate in order to ease the calibration by exchanging specimens with the guarded hot plate. According to the BS standards, this method is applicable only for conductivity range between 0.15 (W/m.K) to 2.0 (W/m.K) which does not include all the range of soil thermal conductivities.

2.7.1.1.3 Heat flow meter apparatus

The heat flow meter method is an indirect technique as the measurements are based on the data of the thermal conductivity of reference materials. It is widely used for estimation of the thermal conductivity of insulating materials and standardized by ASTM C 518 (2004) (Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus). Also, this method can be classified as a comparative, while specimens of known thermal transmission properties are used to calibrate the apparatus. Generally, single or double specimen configurations can be used together with single or double heat flux transducers sandwiched between hot and cold plates. Figure 2-4 shows the configurations of the two types of heat flow meter apparatus.

The calibration of the apparatus should be carried out using reference materials having similar thermal conductivities and the same dimensions as the tested specimen. Once the heat flux through the specimen(s) is measured by the heat flux transducers and calibration factor obtained using reference materials is

accounted, Fourier's law of one dimensional heat transfer can be applied to determine the thermal conductivity of the specimen. Hostler et al. (2009) stated that this method works well for relatively low thermal conductivity. However, it is clear that, for soil measurements, it is difficult to calibrate the flow meter apparatus for all soil thermal conductivities using reference specimens.

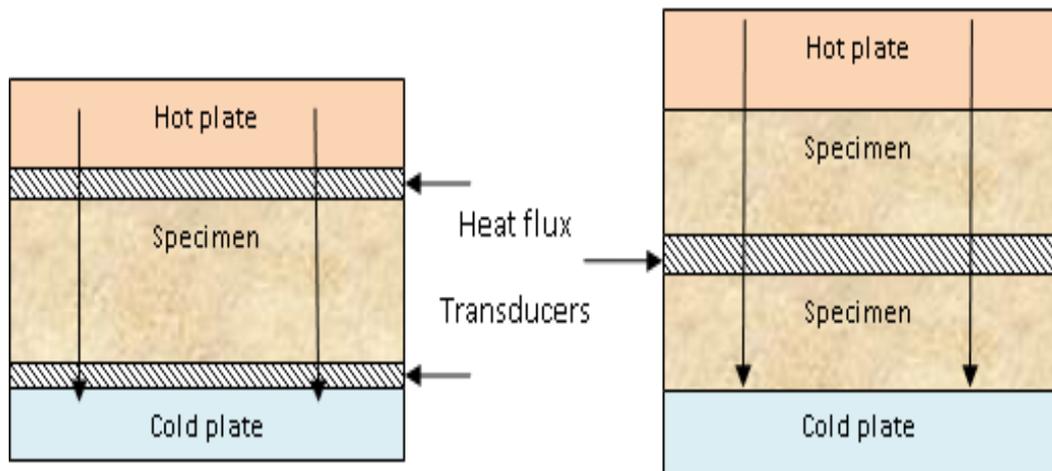


Figure 2-4 Configuration of two types of heat meter apparatus

2.7.1.1.4 Guarded comparative – longitudinal heat flow technique

As described by ASTM E 1225 (2004), a test specimen is clamped between two similar specimens of standard material with known thermal conductivity. Theoretically, in one dimensional heat flow, the power per unit area (heat flux) passed through any cross-sectional area along the column is considered to be equal. A temperature gradient is established in the test stack and temperature drop across each of the three specimens is measured. Lateral heat losses are minimized by using a longitudinal guard having approximately the same temperature gradient and separated from the testing column by suitable insulation (Figure 2-5).

Another configuration can be arranged in which the column consists of a heater disk in the middle between specimen, meter bar and heat sink in each side. In this case, one-half of the power would transfer through each specimen. Various metals can be used as a reference material, but more accurate measurements can be achieved with relatively low thermal conductors due to large differences between thermocouples readings (Tan et al., 2006). It is also remarkable that the

reference specimens should have thermal conductivity as similar as possible to the expected thermal conductivity of the tested specimen (ASTM E 1225, 2004).

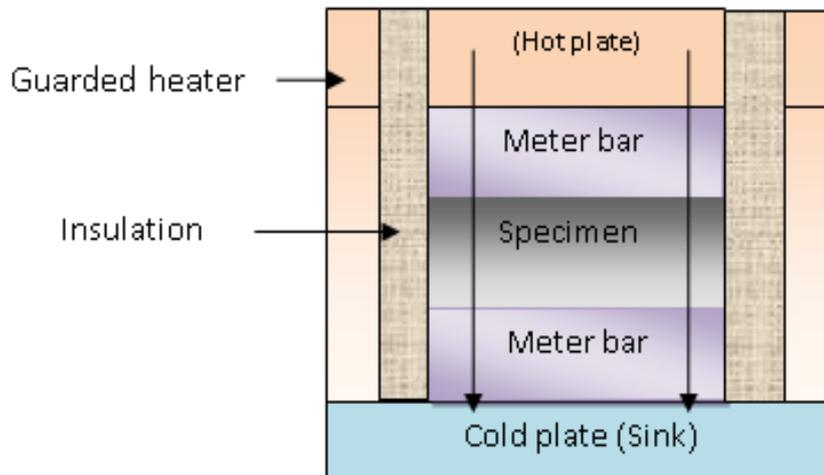


Figure 2-5 : Schematic of Guarded comparative -longitudinal heat flow system

2.7.1.1.5 Concentric cylinder method

This method has been used since the beginning of the last century. The theory behind this method is to create a uniform heat flow in radial direction across the specimen instead of longitudinal direction in hot plate methods. Mostly, the apparatus consists of an inner cylinder which acts as a line heat source when heated and an outer cooling cylinder as a sink. Figure 2-6 shows the schematic of the apparatus.

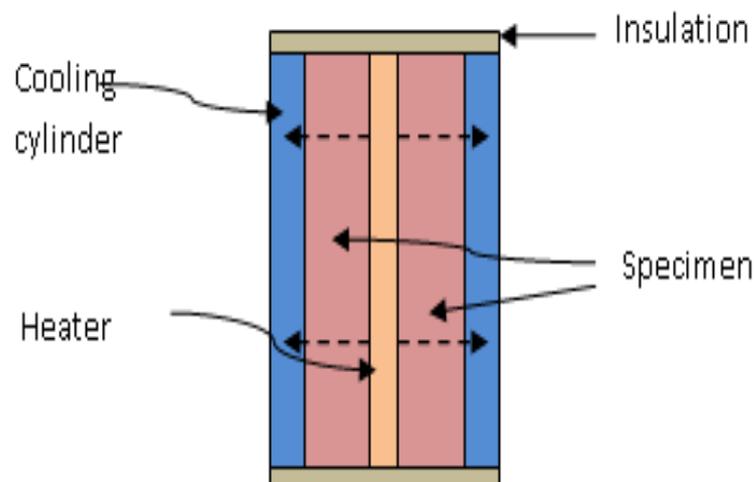


Figure 2-6 : Schematic of concentric cylinder method

The specimen is placed in between where a radial thermal gradient can be obtained due to temperature difference between the two cylinders. In order to reduce the axial heat losses through the edge supports of the cylinders, the apparatus is designed to be very long with respect to the radius. To determine the thermal conductivity of the specimen, Fourier's law of one dimensional radial heat flow can be applied when the system has reached steady state condition. This can be calculated from the input power, length and radius of the specimen, and the temperature difference between the inner and the outer faces of the specimen in the radial direction. This method can be used for high temperatures as well as for frozen situations (Farouki, 1986). The method is also suitable for powder or granular materials. It has been used to measure the thermal conductivity of glass microspheres and aerogel beads at temperatures below 180K and 80K respectively (Barrios et al., 2008).

2.7.1.1.6 Concentric spheres method

This method is used to eliminate the heat losses related to the guarded hot plate and concentric cylinder methods. In this technique, the heat source is at the core of a spherical specimen where all the flow is transferred through the control volume. Figure 2-7 shows a schematic of the apparatus.

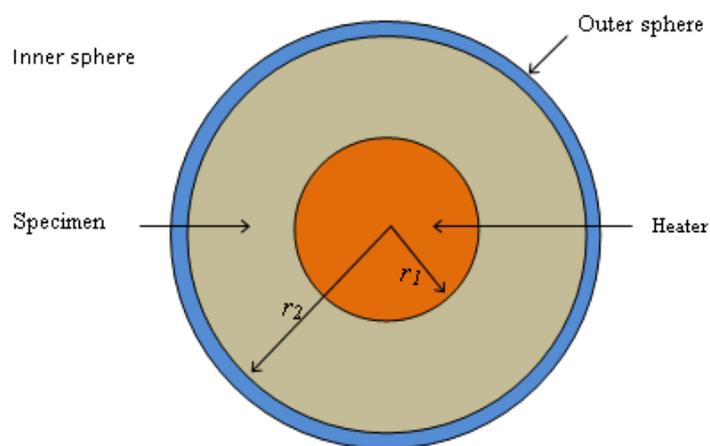


Figure 2-7 : Schematic of concentric spheres method

By knowing the inner and outer radius of the specimen and the temperature drop, Fourier's law of one dimensional radial flow condition can be applied for determination of the thermal conductivity of the soil specimen. Theoretically, this

method can be considered as the most precise technique especially for powder and granular materials. However, spheres are expensive and difficult to prepare (Hamuda, 2009).

2.7.2 Transient state methods

The unsteady state methods (transient methods) measure the thermal conductivity during the transient state. These methods use a line heat source and temperature sensor. They rely on the fact that the thermal conductivity is a function of the rate of the heat dissipation in the surrounding soil. The theoretical solution of conductive heat flow from a line heat source is used to determine the thermal conductivity of the soil sample. These methods are more versatile than the steady state methods because they are easy to perform and require a short measuring time. They also have the potential to directly determining thermal diffusivity, but they are not as accurate as the steady state methods (Mohsenin, 1980). The most popular transient methods are the hot wire, the thermal needle probe (single probe), and the dual probe method. However, probe methods are more common. The probe method has been used for over 50 years. According to Farouki (1986), the first application of the probe were by Van der Held and Van Drunen (1949) to measure the thermal conductivity of liquids, and by Hooper and Lepper (1950) to measure that of soil.

2.7.2.1 Transient hot wire method

In this method, a thin straight wire is embedded in the centre of a soil sample confined in steel container. The wire works as a heat source and the soil sample as the semi-infinite homogeneous isotropic medium. After equilibrium is reached, a constant power is supplied to the wire. Thermocouples are used to measure the radial temperature difference across the soil specimen. The American Society for Testing and Materials has standardized this method (ASTM C 1113) (Standard Test Method for Thermal Conductivity of Refractories by Hot Wire). The thermal conductivity can be calculated from the temperature rise measured at different diameters from the heating wire and the input power as follows:

$$k = \frac{q}{4\pi(T_2 - T_1)} \ln\left(\frac{t_2}{t_1}\right) \quad 2.18$$

where: q is the power per unit length, T_1 is the temperature at time t_1 and T_2 is the temperature at time t_2 .

This method has been used to study the effect of water content and the bulk density of some Jordanian soils (Abu-Hamdeh et al., 2001). Tavman (1996) has used the same technique, however an insulation material with known thermal conductivity was used as a comparative material (modified hot wire method). In this method, the thermal conductivity can be calculated by the following equation:

$$k = F \frac{q}{4\pi(T_2 - T_1)} \ln \left(\frac{t_2}{t_1} \right) - H \quad 2.19$$

where, F and H are specific constants of the wire, and can be determined by materials of known thermal conductivity.

The hot wire methods can be applied to cohesive and small grain size soils where the heating wire is in good contact with the soil (Tavman, 1996; Abu-Hamdeh et al., 2001).

2.7.2.2 Thermal Needle Method (single probe)

The thermal needle method is perhaps the quickest and easiest of the available methods for measuring thermal properties of soil. Hooper and Lepper (1950) used this method to measure the thermal conductivity of soil. They describe the thermal probe and cited two advantages over the guarded hot plate method (ASTM C177). The first was the thermal needle induces less moisture migration and the second was that this method can be used to test undisturbed field samples. It has also the advantages of measuring the thermal resistivity directly from the data set without the knowledge of the heat capacity of the soil. On the other hand, the main disadvantages of this method include that any small variation in the current supplied during the test can result in significant error and contact resistance with medium can have a significant effect (Mitchell and Kao, 1978).

The thermal needle method is based on the theory of a line heat source surrounded by a semi-infinite, isotropic medium. The rate of rise in the temperature of the probe depends on the thermal conductivity of the surrounding medium. When a constant current is applied to the heating element inside the thermal needle, the temperature increase of the probe should be linear when

plotted against the logarithm of time. The thermal conductivity can be calculated as follows:

$$k = \frac{q}{4\pi(T_2 - T_1)} \ln\left(\frac{t_2}{t_1}\right) \quad 2.20$$

where: q is the power per unit length, T_1 is the temperature at time t_1 and T_2 is the temperature at time t_2 .

Chaney et al. (1983) suggested this method as a standard transient method for measuring thermal conductivity of soils and described the apparatus and test procedure in detail. The American Society for Testing and materials (ASTM) has published this method as a standard method (ASTM D 5334, 2008).

The probe method can be used in laboratory specimens of soil from the base of borehole and in near surface soils. The advantages of being simple and rapid has motivated many researchers to adopt it as a method of determination of thermal properties of soil (Mitchell and Kao, 1978; Salomone and Kovacs, 1984; Ewen and Thomas, 1987; Nusier and Abu-Hamdeh, 2003; Abuel-Naga et al., 2009).

2.7.2.3 Dual Probe Method

An additional temperature sensor with known distance (r) from the single probe can be used to measure the thermal properties of soil (Nusier and Abu-Hamdeh, 2003). The theory is based on a solution of the radial heat conduction for infinite-line heat source and isotropic medium at uniform initial temperature. Campbell et al. (1991) developed an instrument that allows measurements several millimetres away from the line heat source. The instrument consists of two stainless steel needles mounted in parallel and separated by a distance r . One needle contains a line-source heater (heater probe) and the other a temperature sensor (sensor probe). After inserting the dual-probe device in soil, a heat pulse is applied to the heater and the temperature at the sensor probe recorded as a function of time. The soil thermal diffusivity and volumetric heat capacity are then determined from the measured temperature response with time at the sensor probe (Welch et al., 1996; Bristow, 1998). Thermal conductivity is calculated as the product of the diffusivity and heat capacity. The heat capacity measured with the dual-probes can also be used together with other basic soil data to calculate the soil's volumetric water content (Bristow

et al., 1993; Tarara and Ham, 1997). This attribute of the dual-probe is one of the main attractions in pursuing development of this heat-pulse methodology.

2.8 Prediction methods

Several soil thermal conductivity prediction methods exist in the literature. These methods vary in applicability, complexity and may be limited to only certain soil types under specific condition. The equations for many of these models were developed from empirical curve-fits to datasets, and thus tend to fit the data for which they were derived very well (Haigh, 2012). All models depend on the thermal conductivity of each individual phase of soil composition and the volume content of each phase to predict the effective thermal conductivity. A brief survey of some of selected prediction methods is given below and some models that widely used will be explained in Chapter 5.

Kersten (1949) developed an empirical equation based on the water content and dry density of the soil. He proposed his equation based on data of five different soil types. Farouki (1986) limited Kersten's method to only soils with intermediate quartz content of about 60% of the soil solids. Also, this model is not suitable for predicting the thermal conductivity at lower water contents.

De Vries (1963) introduced a thermal conductivity model for soils based on Maxwell's equations for the electrical conductivity of ellipsoidal soil particles in a continuous medium consisting of air or water. The model takes a weighted average of the thermal conductivities of each phase of the soil, with a factor taking account of particle shape. Farouki (1986) states that the weighting factors assumed by De Vries in order to match experimental data imply a needle-like shape for the soil particle, unlike most soil particles. Also, the water can be considered a continuous medium only when the volumetric water fraction is above a certain minimum limit.

Johansen (1975) developed a method for determining the thermal conductivity of unsaturated soils based on the dry and saturated thermal conductivities when evaluated at same dry density. He proposed the concept of normalized thermal conductivity and established a simple empirical model that based on the degree of saturation and soil mineral composition. For many soils, Johansen model

provides accurate predictions of thermal conductivity (Tarnawski and Wagner, 1992). According to Farouki (1986), this method was applicable for saturation ratios higher than 20%.

Sakashita and Kumada (1998) proposed a heat transfer model that accounts for the microstructure of compacted bentonites followed by Ould-Lahoucine et al. (2002) who determined the unknown constants included constants in the model using experimental data that have been carried out using bentonite and mixtures of bentonite and silica-sand with different densities, water contents, and sand volume.

Tarnawski et al. (2000a) proposed a theoretically based model for the thermal conductivity of unfrozen soils. The model was modified from a theoretical model for frozen soils that proposed by Gori (1983). This model assumes the soil volume to be represented by a cube with a cubic soil particle at its centre. Increasing amount of water first coats the surface of the soil particle before forming capillary bridges to the six surrounding cells. The performance of this model was improved by Gori and Corasaniti (2002) who added the effect of the increasing the thermal conductivity of the air phase due to the humidity of the model.

Côté and Konrad (2005) modified the Johansen model to eliminate the logarithmic dependence on the saturation ratio, which distorted predictions at low degrees of saturation. This model integrates well the effects of porosity, degree of saturation, mineral content, grain-size distribution, and particle shape on the thermal conductivity of unfrozen and frozen soils.

Lu et al. (2007) also proposed a modification of Johansen's model. They developed an improved model that describes the relationship between thermal conductivity and volumetric water content of soils. With their model, soil thermal conductivity can be estimated using soil bulk density, sand (or quartz) fraction, and water content. According to their findings, the results show that the new model provided accurate approximations of soil thermal conductivity for a wide range of soils.

Chen (2008) proposed an empirical equation of thermal conductivity expressed as the function of porosity and degree of saturation. The model is based on laboratory thermal probe measurements of four sands. The results of 80 thermal

conductivity measurements of sandy soils with wide range of particle size, saturation ratios and void ratios were used to obtain the proposed model.

Cosenza et al. (2003) used numerical modelling to simulate the influence of different parameters such as porosity, solid thermal conductivity and volumetric water content. The equation is applicable at certain ranges of the used parameters. For porosity (n) the range is 0.4 to 0.6, thermal conductivity of the solid fraction (k_s) the range is 2 to 5 ($W/m.K$), and the volumetric water content (θ) the range is 0.1 to 0.4.

Haigh (2012) proposed an analytical model based on unidirectional heat flow through a three-phase soil element. The model analyses the one-dimensional heat flow between two equally sized spherical soil particles of radius R . Two geometric parameters β and ξ are introduced to express the saturation degree and the void ratio respectively.

The Parallel and Series flow equations are also used to set up the variation of the thermal conductivity in two phase soils, the effective thermal conductivity is influenced by the ratio of the thermal conductivities of the two components k_s/k_f and their volumetric ratio x_s/x_f . In two phase condition, the calculated thermal conductivity of a soil should be between the upper limit, obtained from the parallel flow model, and the lower limit, obtained from the series flow model (Farouki 1986). The parallel and series equation, sometimes called the Wiener bounds, consider that all the solids are collected together to form one rectangular block equal to their volume and all the fluid are also collected to form a second similar block. These blocks are then arranged either in parallel or in perpendicular with respect to the direction of heat flow. The minimum value of thermal conductivity occurs for the series distribution in which the solid and the fluid phases are in layers normal to the direction of heat flow. The maximum value of thermal conductivity occurs when the solid and fluid phases are in layers parallel to the direction of heat flow. An important and useful model is the geometric mean model, which assumes random distribution of the different phases in the soil using the average of both the parallel and the series models. This simple model of heat flow is incorporated into many of the methods developed for calculating soil thermal conductivity.

2.9 Borehole thermal resistance

The conventional closed vertical heat exchanger (borehole heat exchanger) consists of three main components. The three components are the water-bearing pipe, grout material around the pipe and soil around the grout. The vertical borehole has cylindrical shape with different diameters and depths. High density polyethylene (HDPE) plastic pipes are usually used with diameter ranges from 20mm to 40mm. It is inserted in a “U” shape, with a “U-bend” at the bottom of the borehole. The next component is the material surrounding the pipe, usually grout, which plays an important role in heat transfer between the soil and the heat carrier.

In a closed-loop vertical heat exchanger, one of the most important factors that influences the efficiency of the system is the thermal resistance of the borehole, which represents the capacity of the borehole to resist the heat flow. It is expressed in $K.m/W$ and must be as low as possible. The most important parameters influencing the borehole thermal resistance are the thermal conductivity of the filling material, the number and the position of the pipes and the pipe thermal conductivity.

The theoretical borehole resistance can be computed as following:

$$R_b = R_{pipe} + R_{grout} \quad 2.21$$

$$R_{pipe} = R_{cond} + R_{conv} \quad 2.22$$

$$R_{cond} = \frac{\ln(D_0/D_i)}{4\pi k_{pipe}} \quad 2.23$$

$$R_{conv} = \frac{1}{2\pi D_i h_i} \quad 2.24$$

$$R_{grout} = \frac{1}{S_b k_{grout}} \quad 2.25$$

where D_i and D_0 are the inside and outside pipe diameters, h_i is the inside film coefficient, k_{grout} is the grout thermal conductivity, R_{pipe} and R_{grout} are the pipe and the grout thermal resistance respectively and S_b is a shape factor depends on the position of the U-tube in the borehole.

Experimentally, the borehole thermal resistance can be determined from the thermal response test (TRT) as following:

$$R_b = \frac{H}{Q} (T_f - T_0) - \frac{1}{4\pi k} \left\{ \ln(t) + \ln\left(\frac{4\alpha}{r_b^2}\right) - 0.5772 \right\} \quad 2.26$$

where, R_b is the borehole thermal resistance, Q is the heat injected in watt, H is borehole depth in meters, T_f is the average of the inlet and outlet fluid temperature, T_0 is the initial ground temperature in °C, k is thermal conductivity in $W/m.K$, α is the thermal diffusivity in m^2/s and r_b is the borehole radius in meters.

The determination of R_b with the TRT is used to verify the impact of thermally enhanced grout on the heat transfer properties of the borehole heat exchanger (BHE) (e.g. Delaleux et al., 2012).

2.10 Thermal grouts

After the installation of U-tube in the borehole, during the construction of the borehole heat exchanger, the borehole is usually backfilled with grout in order to insure good thermal contact with the ground. As mentioned in the previous section, one of the main factors that influence the thermal resistance of the borehole heat exchanger is the thermal resistance of the grout. In other words, the efficiency of the system increases as the thermal resistance of the grout decreases. Conventional bentonite borehole grouts have been shown to present the main thermal resistance (65%) followed by the HDPE tube wall (35%) (Delaleux et al., 2012). Therefore, the performance of the ground heat exchanger can be improved by increasing the thermal conductivity of the grout (Lee et al., 2010). The optimization of the ground heat transfer by improving the design and increasing the grout thermal conductivity allows for reduction in the size of the ground-loop heat exchanger and can result in a considerable cost saving in the total cost of installation (Allan and Kavanaugh, 1999; Remund, 1999).

2.10.1 Enhancement of thermal conductivity of grout

Thermal conductivity of a material can be enhanced by addition of a material with a superior thermal conductivity material. It has been ascertained that sandy soil has a higher thermal conductivity than loamy soil at any given saturation and

density (Abu-Hamdeh et al., 2001). This is as a result of the mineralogy of sandy soil having superior thermal conductivity to that of clay soil. Some studies have taken advantage of using silica sand as an additive to enhance the thermal conductivity of cement and bentonite based grouts (Allan and Philippacopoulos, 1998). XU and Chung (2000) reported that when sand was added to cement paste the thermal conductivity went up by 22%. The conventional grout in use is mainly bentonite based. However, bentonite based grout has relatively low thermal conductivity and is susceptible to shrinkage and cracking due to moisture losses (Allan and Philippacopoulos, 1998). This has pushed researchers toward developing a variety of grouts with higher conductance, such as cement based grouts etc.

Various blends of basic mixes of cementitious grouts have been made to improve the thermal conductivity (employing the hot wire method) of grouts. Most of the work done on enhancement of thermal conductivity of grouts has concentrated on bentonite and cement-sand grout. Cement-sand grout is more efficient and cost effective to be used as a thermal grout than bentonite based grout. For example, using cement and sand in a ratio of 1: 2.13, the thermal conductivity of the mix at 28 days curing ware 2.43 $W/m.K$ and 2.16 $W/m.K$ in saturated and unsaturated state respectively. These values are triple that of high solid bentonite (0.75-0.8 $W/m.K$) and neat cement grout (0.8-0.87 $W/m.K$) (Allan and Philippacopoulos, 1998).

There are other materials that have been used for grouting application such as Pulverised Fuel Ash (PFA) because of its relative abundance and good workability, permeability and low shrinkage. But this type of material has not been utilised much as a thermal grout.

2.10.2 Permeability

This is the second key parameter in thermal grout applications. Permeability is an important in GSHP applications from contamination aspects especially where ground water is expected. The ground water can be contaminated by the chemicals composing the grout. According to Cerutti (2010), the permeability of grouts for used with GSHP must not exceed $1.0 \times 10^{-5} m/s$. Permeability is influenced by curing time and mix composition. This was investigated by Fall et

al. (2009) in an effort to know what factors affect the permeability of cemented paste backfill; it was concluded that prolonging time of curing and increasing binder content (decrease in W/C ratio) results in a decrease in permeability. In their research work, they got permeability values of the order of 10^{-2} - 10^{-4} m/s. for the cemented paste backfill and were lowest at 90 days. Akbulut and Saglamer (2004) carried out the falling head permeability test on grouted samples obtained by addition of additive such as fly ash, clay and silica fume to improve the physical properties and permeability of sand. It was found out that all the additives produced improved physical properties and decreased permeability (10^{-3} - 10^{-5} m/s) of the grouted sand samples.

The texture, gradation and mineralogy of materials used for grouting also affects permeability. Sandy soils are usually very porous with a high permeability, except where fine soils are in high percentage. The usual practise is to use lime, cement or bentonite for thermal grouting due to their low permeability. Allan and Philippacopoulos (1998) worked on improving thermal conductivity of grout using sand and obtained a low coefficient of permeability (1.93×10^{-5} m/s) for cement-sand grout which was higher than neat cement grout (6.3×10^{-4} - 1.06×10^{-3} m/s). PFA added to cement grout improves its permeability considerably because of its small particle size, shape and pozzolanic reaction (UKQAA, 2006). It means that PFA-based grout will be promising to meet the waste containment criterion of 1.0×10^{-5} m/s.

2.10.3 Groutology flow

In GSHP application the flow dictates how easily grouts could be pumped to backfill the borehole. Factors that affect flow of grouts are the amount of coarse or fine aggregate and the ratio of water to cementitious materials. Higher amounts of coarse aggregate with large quantities of water cause segregation. Fines present in a mix reduce the chances of segregation, but this may cause the pumpability to deteriorate when there is not sufficient water in the mix. In order to avoid segregation and to boost pumpability, the amount of water in the mix is reduced and additives added. Adding fly ash or PFA to cement grout leads to a reduction in the flow time of the grout (Mirza et al., 2002) and this calls for additional amounts of water to achieve desired flow.

But excessive water in grout may cause segregation and bleeding, especially if coarse aggregates are to be used, however bleeding may not cause serious problem if it is not excessive. Plenty water can equally affect thermal conductivity particularly when grouts are to be used for thermal purposes (Allan and Philippacopoulos, 1998).

Flow of grouts could be improved without the need for more water in the grout mix. Plasticizers/ super plasticizers are commonly used for this purpose. However, use of plasticiser/ super plasticizer also affects the thermal conductivity of grouts (Allan and Philippacopoulos, 1998). PFA grouts with a flow value of 450mm offers adequate pumpability in most situations (UKQAA, 2006).

Chapter 3 : Steady-state thermal conductivity; new apparatus

3.1 Introduction

Most of the steady-state methods used to measure thermal conductivity are based on the application of the Fourier's law. This theory was used as the principle in the design of the guarded hot plate method which is considered as the most accurate method in measuring thermal conductivity. However, the guarded hot plate method is used to measure the thermal conductivity of insulation materials. The function of the proposed thermal cell is to measure the thermal conductivity of soils. This includes samples prepared in laboratory as well as samples obtained from routine soil investigation (U100 samples). The design is based on the application of the Fourier's law of one-directional heat conduction at steady-state condition. Before attempting to design the new apparatus, several steady-state experimental devices that have been used to measure thermal conductivity of soils were studied. As a result, a number of factors associated with the apparatus as well as specimen(s), which can yield incorrect results if not appropriately considered, are distinguished. The level of the accuracy of these devices depends on how the designers can control these factors and ensure that all the parameters used in the calculations are reliable.

This chapter presents the basic concepts behind the design and the test theory for the new thermal conductivity apparatus followed by the description and the function of the cell parts. It also presents different test procedures and samples preparation methods for different types of soils including field and reconstituted specimens. In addition, different experimental tests are conducted to evaluate the performance of the new apparatus and to assess the effect of the boundary conditions on the measured thermal conductivity. Finally, the results obtained from the experimental part will be discussed.

3.2 Design and description

3.2.1 Basic concepts

The purpose of the present apparatus is to measure the thermal conductivity of soils including samples obtained in routine ground investigation. This requirement limits the shape and the size of the specimens to that typical field samples (U100 samples). It is also required that the apparatus should be simple and robust and able to operate over a range of temperatures covering natural ground temperatures with suitable test procedures that can be applied to different types of soils under different conditions.

The design is based on the application of Fourier's law of one-dimensional heat conduction under steady state condition. The new apparatus uses the principle of generating a thermal gradient through cylindrical soil specimen parallel to the longitudinal axis. A heat source (heater disc) having the same cross sectional area is inserted in between two identical specimens to create a uniform temperature at one end of the specimens. Two aluminium discs, one at the unheated end of each specimen, are used to dissipate the heat. Using the equation developed by Fourier for heat conduction with one dimensional heat flow at steady- state condition, the effective thermal conductivity k can be determined as follows:

$$k = \frac{qL}{2A\Delta T} \quad 3.1$$

where, q is the rate of heat transfer in watts, L is the specimen length in meters, A is the cross-sectional area in meters and ΔT is the temperature drop across the specimen length. The factor of two in the denominator arises because under ideal condition the heat flux from the central plate is equally shared between the two specimens.

To minimize the radial heat loss there are three ways; the first is to make the diameter to thickness ratio as large as possible. However, this method cannot be used for samples obtained from routine ground investigation. Also, small thicknesses do not represent the homogeneity of the soil especially for samples with large size fractions. The second is to surround the edge of the specimen with insulation. In this case, the amount of the radial loss depends on the effectiveness

of the insulating material. The third way is to create a thermal gradient surrounding the specimen close to that generated by the heater through the metering area of the specimens. In this case, it is difficult to control the heat exchange between the two gradients. Therefore, to reduce the lateral loss in this apparatus, a combination between the second and the third options is proposed. This can be done by surrounding the specimen with insulating material and surrounding the insulating material with a thermal gradient close to the main one. In this case, the effect of the ambient temperature can be eliminated and the radial heat loss can be minimized by controlling the guarding thermal gradient. The external thermal gradient can be generated by several ways. The simplest is to pump hot water through a spiral tube surrounding the outer face of the cell, the gradient can be produced by controlling the temperature and the discharge of the water. Figure 3-1 shows the schematic diagram for the proposed thermal cell.

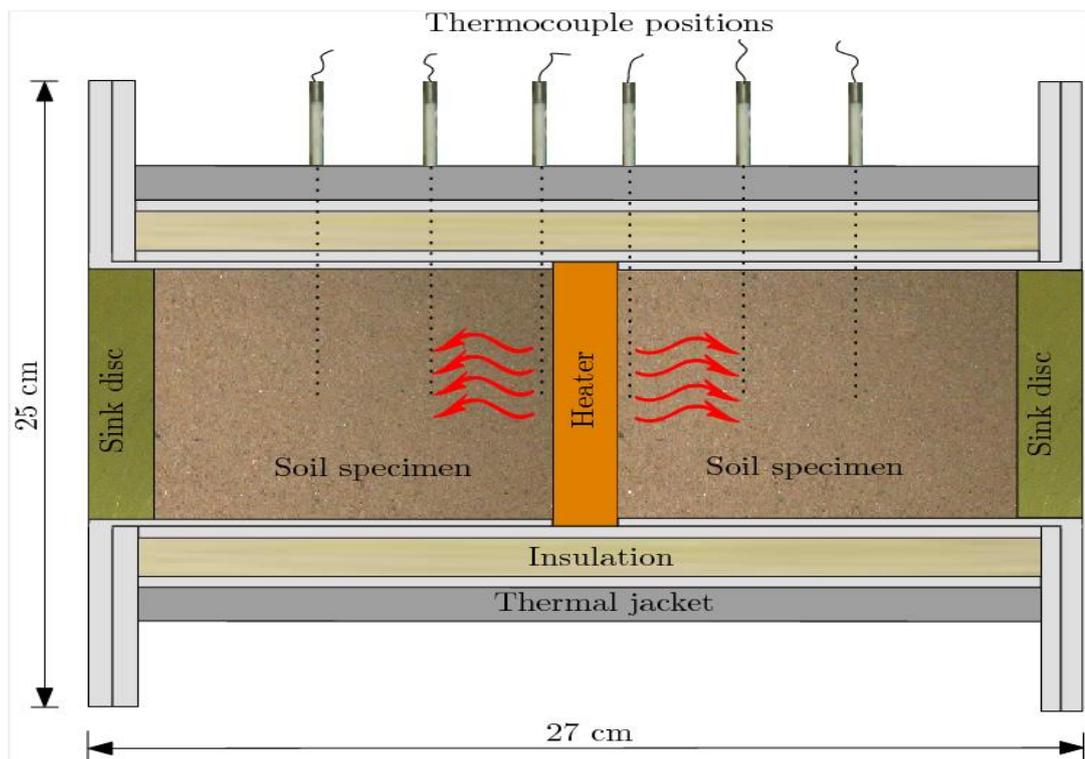


Figure 3-1 : Schematic diagram of the new thermal cell

3.2.2 Factors controlling the design

3.2.2.1 Unidirectional heat flow

Since the design is based on the application of Fourier's law of one-dimensional heat conduction under steady state condition and from the definition of the one dimensional steady state, it is assumed that the heat flow is considered to be in one direction, which means that no lateral heat transfer takes place from the specimen. Practically, it is difficult to achieve this condition because of the ambient temperature interference (ATI) which produces additional radial temperature distribution to the desired axial temperature gradient (Zhou et al., 2006). It is essential to consider the effect of the ambient temperature on longitudinal and radial heat flow. The common method to minimize the effect of ambient temperature is to use an insulation layer. In fact, to establish unidirectional heat flow, it is required to have a mechanism that separates and controls the two kinds of the heat flow (longitudinal and radial heat flow). In order to minimize the effect of ATI and to maximize heat flow in one direction, the new apparatus is designed to control the radial heat flow by constructing a new layer with adjustable temperature (thermal jacket) and to keep the temperature of the sink disc near ambient temperature. The level of the thermal jacket temperature will control the amount and the direction of the radial heat flow along the specimen length. As the temperature of the thermal jacket is kept below the minimum specimen temperature heat will flow from the specimen to the ambient. The amount of this heat depends on the difference in temperature between the specimen and the ambient. On the other hand, heat will flow from the thermal jacket into the specimen as the thermal jacket temperature is kept higher than a certain level of temperature. This means there is a place in between where there is no radial flow occurs.

3.2.2.2 Base heat loss

Another source of heat leakage that in some designs can negatively contribute to the measurement is the base heat loss. To eliminate the effect of the base heat loss, in the new thermal cell the heater is inserted between two identical specimens. Consequently, the input power used in the calculations is divided by two. However, in this case the symmetry of the specimens and the apparatus

itself are influential because any asymmetry or inhomogeneity will lead to unequal heat passes through the two specimens.

3.2.2.3 Heat uniformity

The heat flux, which is defined as the amount of the heat that passes through a unit cross-sectional area, should be uniform across the specimen. To achieve this, the heater and sink discs must be as flat as possible and made of highly conducting and emissive material. It is important at this point to highlight the effect of the contact resistance which is defined as the resistance to heat transfer at an interface between adjoining objects of different shapes or roughness due to poor physical contact.

3.2.2.4 Thermocouples

The number, positions and the directions of the measuring thermocouples are also very important, because the thermal conductivity of the thermocouple material is very high compared with the soil. This may cause unpredictable heat flow through the thermocouples if not appropriately considered.

3.2.2.5 Specimen length

As the diameter of the specimen is limited to the U100 tube (103mm), the length of the specimen has a large effect on the amount of radial heat loss. Short specimens are preferable. However, homogeneity cannot be ensured especially for samples obtained from routine soil investigation, as natural samples will often have variable composition and particle size distribution.

3.2.3 Apparatus description

The main body of the cell is made of acrylic. The low thermal conductivity of acrylic helps in reducing the radial heat loss and its stiffness allows specimens to be compacted during the preparation if required. Three main parts constitute the cell body: the middle is the insulating cylinder which is made from double-wall tubes separated by insulation material (polyurethane foam). The other two parts of the cell body are the two identical acrylic specimen cylinders; each cylinder has the same cross-section as the U100 sampling tube. The details of each part of the thermal apparatus are explained as follows:

3.2.3.1 The acrylic body

Three main parts constitute the cell body: the middle is the insulating cylinder which is made from double-wall tubes separated by insulation material (polyurethane foam) (Figure 3-2 a). The inner, the outer diameter and the length of the cylinder are 110, 200, and 240 mm respectively. Both ends of the tubes are completely sealed together with 270×270×15mm acrylic cover plates with 110mm centre holes. The other two acrylic parts of the cell body are two identical specimen cylinders (Figure 3-2 b). Each cylinder has length of 127 mm and inner diameter of 103 mm. The outer diameter is the same as the inner diameter of the insulating cylinder. Acrylic cover plates of 270×270×15mm with centre holes of 103 mm, instead of 110 mm, are fixed onto one end of each cylinder. These cylinders are stiff enough to sustain any required compaction during specimen preparation stage. One advantage of this design is that these cylinders can be easily remanufactured if damaged or deformed during the life of the apparatus.

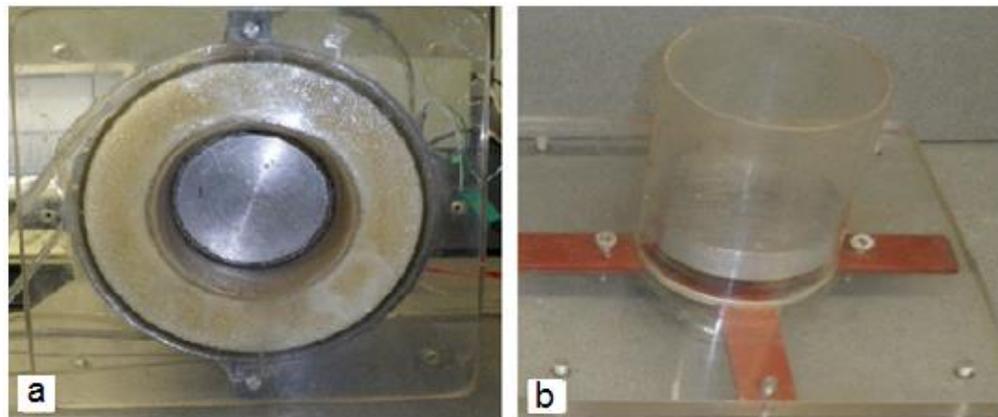


Figure 3-2 : (a) the insulating cylinder (b) The specimen cylinder

3.2.3.2 The heater disc

An aluminium disc with the same diameter as the inner diameter of the insulating cylinder (103 mm) and 20 mm thickness is oriented and completely fixed in the middle inside the insulating cylinder. The temperature of the disc is raised by a DC cartridge rod heater that can be easily inserted into the disc through a drilled hole in the acrylic body of the cell. The input power can be adjusted to give the desired temperature. When using a DC cartridge with built in thermocouple, the

difference in temperature between the face of the disc and the cartridge rod is negligible. However, more accuracy is adapted by measuring the temperature at all points along the specimen length using same type of thermocouples to avoid any errors due to differences in manufacturing specifications.

3.2.3.3 Sink discs

Two movable aluminium discs with diameter of 103mm and thickness of 20mm are positioned in the outer side of each specimen cylinder (Figure 3-3 a). In addition to the main function of these discs, dissipating the heat from the specimens, they are used to apply a gentle pressure on the specimen to insure a complete contact between the heater disc and the soil in case of field or laboratory consolidated samples. Moreover they can be used to control the volume of the soil when the specimens are laboratory prepared. A number of small holes are drilled in the sink discs in order to place the thermocouples, if needed, to the desired positions within the soil specimens. The two discs are held by a steel holder plate with centred adjustable cylindrical bolt. These bolts are used to adjust the position of the sink discs and to apply the pressure required to reach the desired density especially for non-cohesive dry soils. To insure the symmetry of the pressure exerted on each specimen, free long studs through small holes in the acrylic plates are used to push the two plates holding the sink discs toward each other.

3.2.3.4 The thermal jacket

The function of the thermal jacket is to minimize radial heat losses and to maximise heat flow longitudinally. The heat barrier (thermal jacket) can be established using two separated plastic tubes spiralled around the insulating cylinder with one middle inlet and two side outlets (Figure 3-3 b). The length of each tube is about 7 meters which allows the hot water to cool down as it flows along the tube producing the desired temperature gradient. Using a controlled temperature water bath and a circulating pump (Figure 3-4 a), the temperature of the circulated water can be controlled to achieve the desired thermal gradient.

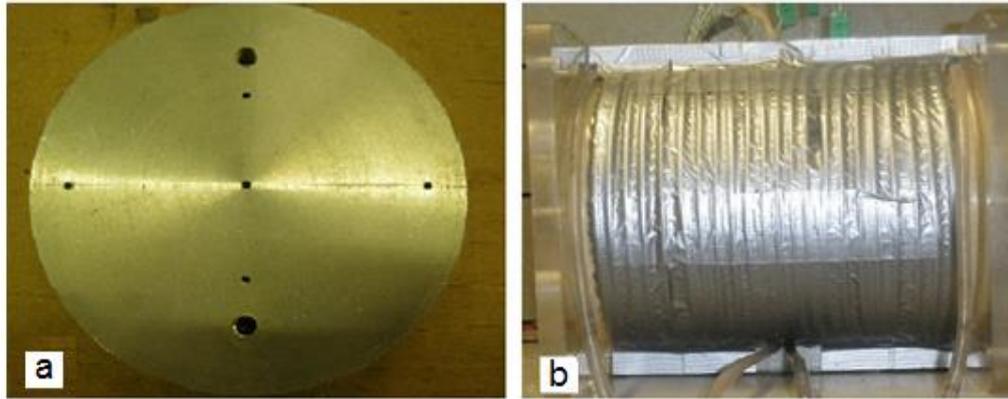


Figure 3-3 : (a) sink disc (b) Thermal jacket

3.2.3.5 Thermocouples

The theory of the thermocouples is simple. Any two types of metal will produce a voltage difference at given temperature. However, there are some standard types of materials that are used to give a predictable output voltage. The relation between the temperature and the output voltage is nonlinear and complex. Therefore, analogue methods of linearization are used to express the outputs as a temperature reading.

In thermal tests, thermocouples are needed to measure and monitor the temperature gradient across the specimen. K-type stainless steel probe thermocouples with a diameter of 1.5mm are used for this purpose. To determine the thermal conductivity of any specimen according Fourier's law, it is necessary to measure the temperature at least in two points along the longitudinal axis. However, for more accuracy and to estimate the amount of heat loss due to lateral heat flow, the temperatures at four positions in each specimen are detected. These points are located at 0, 30, 60, and 80mm from the heater along the longitudinal axis. The thermocouples can be inserted into the specimens laterally via small holes drilled through the body of the cell.

3.2.3.6 Water circulation system

The water circulation system comprises water bath, temperature regulator, plastic tub and water pump (Figure 3-4 a). The temperature of the circulating water can be adjusted to the desired level using the temperature regulator. The hot water is pumped to the thermal jacket through plastic tub using the water pump. The speed

of the water through the plastic tub can be controlled to obtain the desired gradient along the thermal jacket.

3.2.3.7 TC-08 Pico-logger

The thermocouples are connected to a TC-08 Pico-data logger (Figure 3-4 b). The specifications of this instrument showed that the error in the temperature reading can reach $\pm 0.2\%$. The Pico-logger software is able to record at different time intervals ranging from few seconds to several hours and can take continuous readings for several days. A total of eight thermocouple readings can be recorded simultaneously.

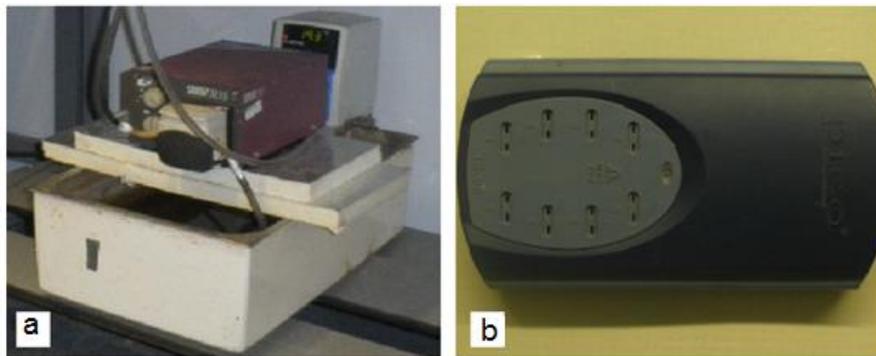


Figure 3-4 : (a) Water circulating system (b) Tc-08 Pico-logger

3.2.3.8 DC current source

A DC laboratory bench power supply type TS 3022S is used as a source of power required to generate heat flow through the specimens (Figure 3-5 a). This model can provide constant voltage in an appropriate range of 0 to 12 V and current between 0 and 2 A. The output voltage can be adjusted by fine and coarse controls to enable precise setting of voltage and current levels.

3.2.3.9 Steel holder plates

Two steel plates are used to hold the sink discs in the specimen cylinders (Figure 3-5 b). Each plate is provided with an adjustable cylindrical bolt to accommodate different specimen thickness. Another function of these plates is to apply any symmetrical pressure required on the specimens through long steel studs connecting the two cylinders.

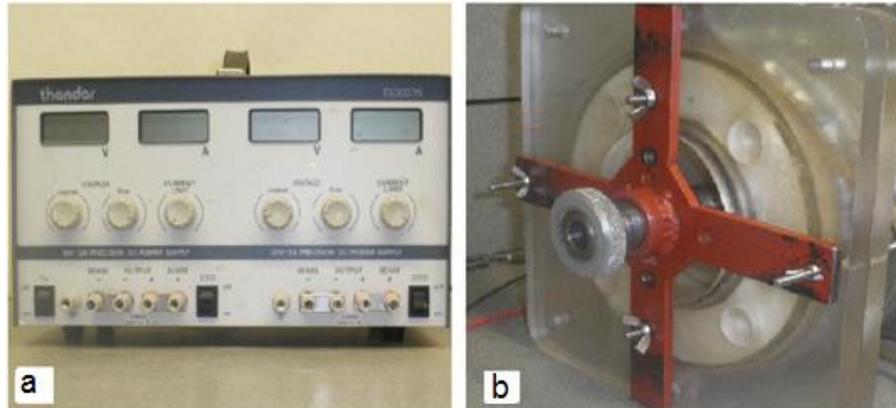


Figure 3-5 : (a) DC current source (b) Steel holder plates

3.2.3.10 Constant temperature room

Since the steady state condition can take a long time to achieve, in some cases it needs days, it is important to keep the ambient temperature constant throughout the experimental period. To avoid any change in ambient temperature, a room with constant temperature controller is used. The level of the ambient temperature is very important as it is in direct contact with the sink discs and separated from the cylindrical surface of the cell by the thermal jacket. The temperature gradient along the specimen length is inversely proportional to the ambient temperature.

3.3 Specimen preparation and procedures

The apparatus was designed to test both undisturbed and reconstituted samples. In all cases, two identical specimens are required for each thermal conductivity test. The weight, volume and water content for each sample are determined before the test. The preparation of specimens depends on the condition of the soil to be tested.

3.3.1 Field samples (undisturbed samples)

The field samples are obtained from routine field investigation (U100 samples). If the soil is stiff enough to be pushed out from the sampling tube without any disturbance, the preparation of the specimens can be carried out by cutting two sub-samples and trimming to the desired length (90 to 100mm). It is important that the two specimens should be identical and have flat parallel ends. The two

specimens are then slotted into the specimen cylinders (Figure 3-6). The weight and the volume of the specimens are recorded to calculate the bulk density and any other parameters may require. The trimmings are used to measure the water content. If the soil is not stiff enough to be pushed out from the sampling tube without disturbance, the sampling tube with the soil can be cut and inserted directly into the insulating cylinder. In this case, the positions of the thermocouples should be marked on the sampling tube and drilled.

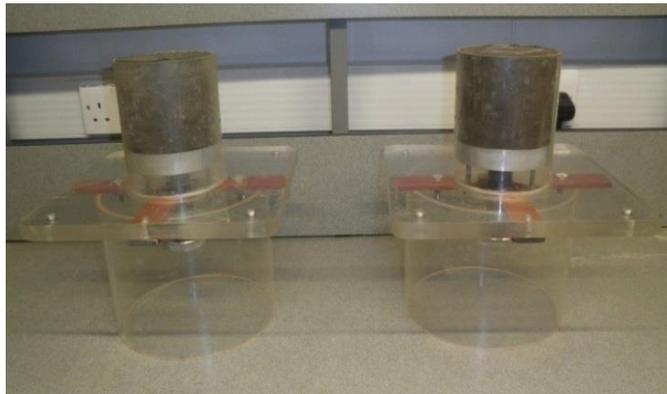


Figure 3-6 : Specimen cylinders containing undisturbed field samples

3.3.2 Reconstituted samples

Laboratory-prepared samples can be prepared by two different methods depending on the type of sample soil. The first method is related to fine grained soils (cohesive) such as clays and cohesive silts, and the second method is related to coarse grained soils (non-cohesive) such as sands and gravel.

3.3.2.1 Cohesive soils

For cohesive soils, the specimens are prepared by mixing the dry soil with water in a blender to the desired water content. The water content should be higher than the liquid limit of the tested soils to produce a homogeneous and saturated specimen.

The slurry-like mixture obtained is then fully consolidated using a consolidation cell having same cross-section area as the specimen cylinder (Figure 3-7). In this step, it is important to apply the stress gradually to prevent a surge of slurry around the piston. This step may take several days to reach fully consolidation condition. At this point, the load is then released and the sample extruded.

The obtained sample is then cut to the required length (90 to 100 mm) with flat parallel ends. The specimen is weighed and its diameter and length are measured. The remaining parts of the sample are used to evaluate the water content. For each thermal conductivity test, two identical specimens are prepared in the same way.



Figure 3-7 : The consolidation cell

3.3.2.2 Non-Cohesive soils

Non-cohesive soils are prepared according to their water content.

To prepare a dry soil sample, the specimen is oven dried for 24 hours before being tested. This is to remove any moisture from the soil as the thermal conductivity of soils is very sensitive to the water content especially at low percentages. After allowing the sample to cool down, the required specimen mass is determined according to the desired dry density. Two equal masses of dry soil are prepared. The specimen cylinders are inserted and fixed into the insulating cylinder without sink discs and steel plate holders. The soil mass is directly funnelled into the thermal cell and the sink discs are then placed and supported by the steel plates. To obtain the desired density, the sink discs are pressed towards each other to reach the predetermined positions which can be done by rotating the movable steel bolts that are fixed at the steel holders.

For non-dry soils, it is essential to determine the water content required to obtain the desired degree of saturation for a certain dry density. Different degrees of

saturation at same dry density (same porosity) can be obtained by changing the water content for a defined mass and volume of soil. By setting the required degree of saturation and the porosity (dry density can be represented by porosity) of the soil specimen, the mass of the dry soil and the water content required to produce this soil specimen condition can be determined using the following relations:

$$e = \frac{n}{1-n} \quad 3.2$$

$$w = \frac{e \cdot S_r}{G_s} \quad 3.3$$

$$\rho_d = \frac{G_s \cdot \rho_w}{1+e} \quad 3.4$$

$$\rho_{wet} = \rho_d(1 + w) \quad 3.5$$

where e is the void ratio, n is the porosity, w is the water content, S_r is the degree of saturation, G_s is the specific gravity of the solid particles, ρ_w is the water density, ρ_d is the dry density of the soil and ρ_{wet} bulk density of the soil.

After determining the amount of water content and the dry mass required to obtain the predefined condition (degree of saturation and porosity), the soil sample can be prepared by mixing the water with the dry soil. By knowing the volume of the specimens, the required wet mass can be calculated. The positions of the sink discs in the specimen cylinders are adjusted to maintain the desired volume. The soil is then poured and compacted in three layers. Then the top surface is levelled carefully with minimum disturbance to the soil (Figure 3-8). These steps should be repeated if the actual compacted soil mass was different to the theoretical value. Also, the actual water content should be measured to insure that it is the same as the theoretical value.

For saturated specimens, it is important to keep the moisture content constant along the test piece. This can be achieved by sealing the contact lines between the sink discs and the acrylic cylinders as well as the thermocouple contact points and by using as low a temperature gradient as possible.

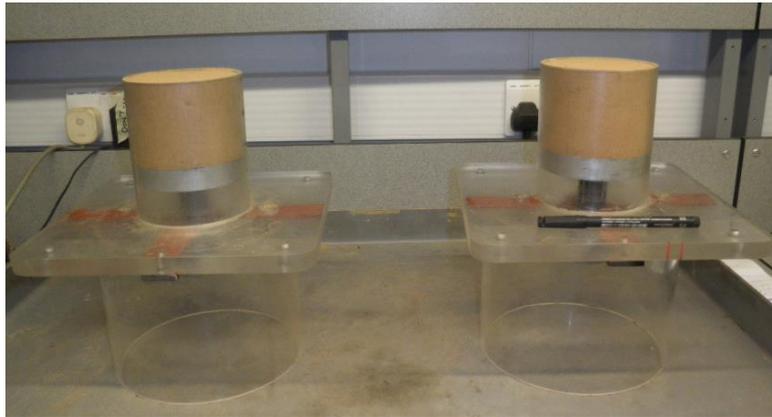


Figure 3-8 : Specimen cylinders containing sand samples

3.3.3 Test set-up and procedure

During all experimental work and before starting the test it important to calibrate the thermocouples as the thermal conductivity calculation is very sensitive to the temperature difference between the measuring points. A simple and effective method was adopted in this research in which the tips of the thermocouples were immersed in a constant temperature water bath. The difference in temperature readings can be adjusted to the temperature of the water bath using the Pico-logger software.

3.3.3. 1 Placing of specimens

After the preparation of the specimens was completed, the two specimen cylinders containing the soil samples are then slotted and fixed into the insulating cylinder (Figure 3-9).

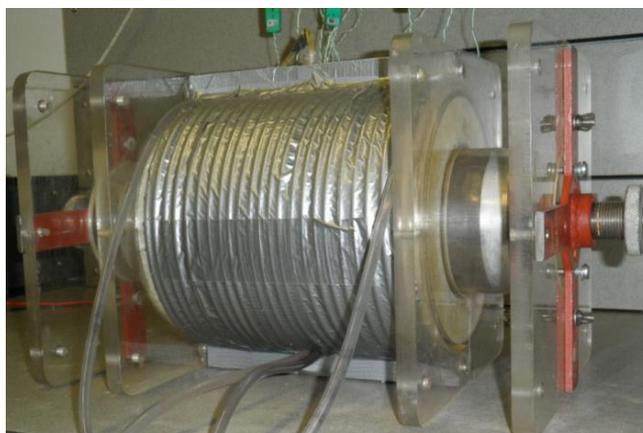


Figure 3-9 : Placing of specimens into the thermal cell

This can be done by means of short studs used to fasten the two acrylic cover plates from each side. The length of the specimen cylinders is designed to ensure complete contact between the heater disc and the two specimens when they reach the final position inside the insulating cylinder. The free long steel studs can be used to apply any necessary equal pressure on both specimens. In some undisturbed soil specimens, which contained gravel that cannot produce a smooth surface, a thin layer of thermal grease can be applied to the ends of the specimens to reduce the contact resistance.

3.3.3. 2 Power input selection

The power input to the specimen for any test was selected so that the temperature did not exceed the safe limit of the acrylic material (60 °C). The power selection depends on the required temperature gradient. Also, it depends on the thermal conductivity of the soil, the higher thermal conductivity the higher power input required to produce the same average specimen temperature. A clear example is the testing of dry and saturated soils. In order to get an adequate temperature gradient, the required power input for the saturated soil specimen is approximately twice that for the dry specimen at the same dry density. This can be explained due to the high thermal conductivity of saturated soil compared with its thermal conductivity at dry condition.

3.3.3. 3 Thermocouples, Pico-logger and water pump

For each specimen, three thermocouples are pushed through the lateral holes to reach the centre of the specimen (Figure 3-10). Another two thermocouples can be used to measure temperature at the ends of the specimen by inserting them through premade holes in the sink discs.

For hard specimens, lateral holes should be drilled corresponding to the positions of thermocouples. Care should be taken to ensure that the thermocouples tips are in good contact with the specimen inside the drilled holes. A small amount of conducting paste can be used to ensure good contact with specimen.

The Pico-logger and the DC power supply are then connected to the thermocouples and to the heater respectively. The water pump is then connected to the thermal jacket and the water bath temperature is raised to the desired level. The temperature of the water should be higher than the ambient temperature and

not exceeding the average specimen temperature. The ambient temperature is then adjusted to the desired level by the room temperature controller and the whole set is kept to reach thermal equilibrium. Figure 3-11 shows the complete set-up of the thermal conductivity test apparatus.

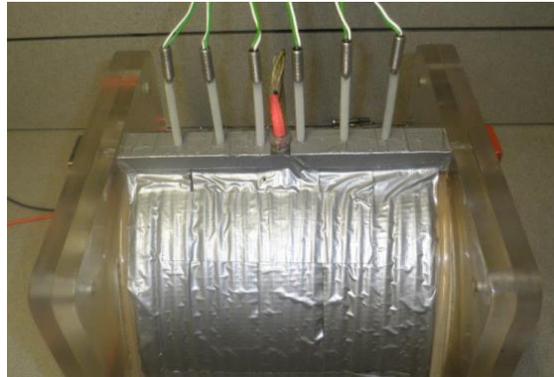


Figure 3-10 : Six thermocouples inserted to the specimen centre

After thermal equilibrium has been reached and before starting the test, it is important to check the thermocouple temperature readings. All thermocouple readings should be equal to the ambient temperature. The Pico-logger software allows correcting any differences that can be noticed between the thermocouples readings and the ambient temperature.

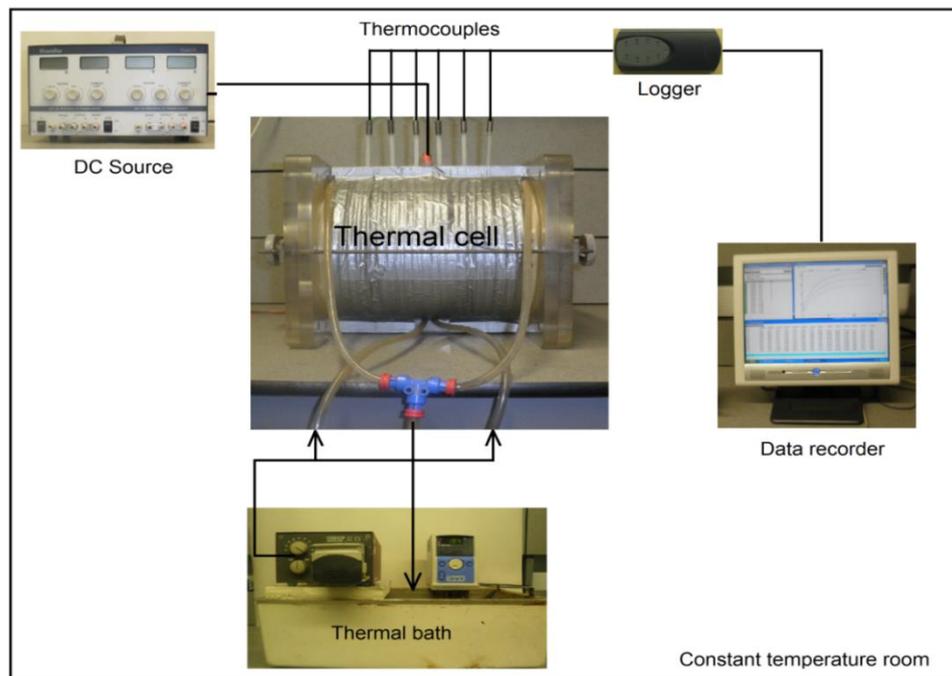


Figure 3-11 : Complete set-up of the thermal conductivity test apparatus

3.3.3. 4 Starting the test

The test is started by switching on the DC power supply simultaneously with starting the water pump and the Pico-logger software. The quantity of the power q in watts is controlled by changing the voltage and / or the current in the DC power supply. It is assumed that the two specimens are identical and that symmetry is achieved. If this is not the case the temperature readings at any two symmetrical points would be different. A very small variation can be accepted as the average values are used in the calculations. The power is maintained until the steady state condition is reached. The steady state condition can be identified from the continuous constant temperature readings of the thermocouples.

3.3.3. 5 Calculations and correction method

After the steady state reached, the output temperature of each thermocouple can be plotted and tabulated versus time. Figure 3-12 is a typical temperature verses time profile.

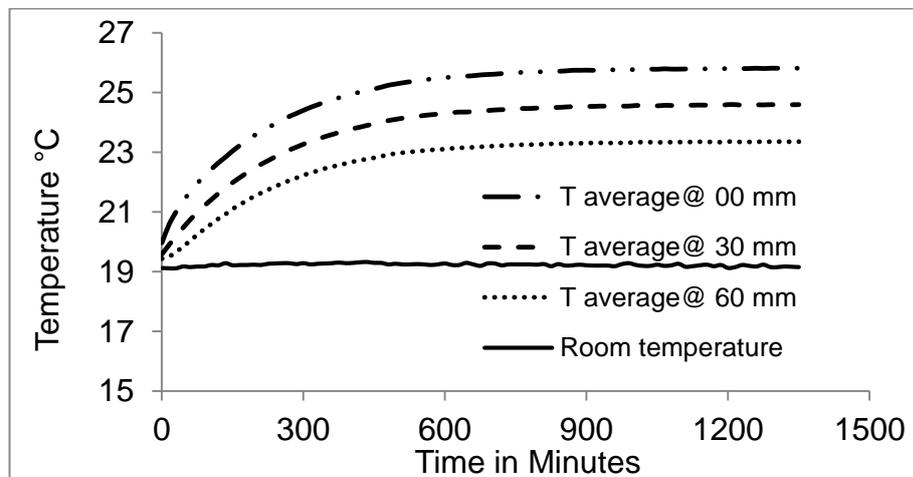


Figure 3-12 : Typical temperature versus time profile.

The difference in temperature between any two points is used to evaluate the thermal conductivity of the tested specimens. The effective thermal conductivity k can be determined using equation 3.1 that developed by Fourier for heat conduction with one dimensional heat flow at steady-state condition.

The temperature data recorded by the Pico-logger software can be processed and analyzed using basic tools provided by the software. The final data are then

transferred to an Excel worksheet to allow the test results to be analyzed and interpreted.

According to Fourier's law of one dimensional heat flow at steady state condition, the temperatures at two points are required to calculate the thermal conductivity of any sample. However, this assumes that the heat flux is constant along the interval between the two points and does not consider that radial heat losses may occur. The ideal condition (no radial losses occur) can be identified when the calculated thermal conductivities using different specimen lengths in Fourier's conduction equation (Equation 3.6) are the same. At least the temperatures at three points are required to identify the state of the radial losses along the specimen length. For that reason, the thermal cell was designed to allow the temperature be measured at different distances from the heater.

In this experimental work the temperature is measured at distances 00, 30, and 60mm from the heater. The first thermal conductivity is calculated using temperatures at 00 and 30 mm with $L= 30$ mm. the second thermal conductivity is calculated using the temperatures at 00 and 60 mm with $L= 60$ mm. The thermal conductivity results are plotted against their corresponding distances from the heater. The state of the radial heat losses along the specimen length can be identified by the slope of the line. If the line is not horizontal (which means an amount of radial heat losses took place during the test period) a correction step can be applied. The corrected thermal conductivity is the value at zero length that can be extrapolated from the equation of the line, Figure 3-13 is an example.

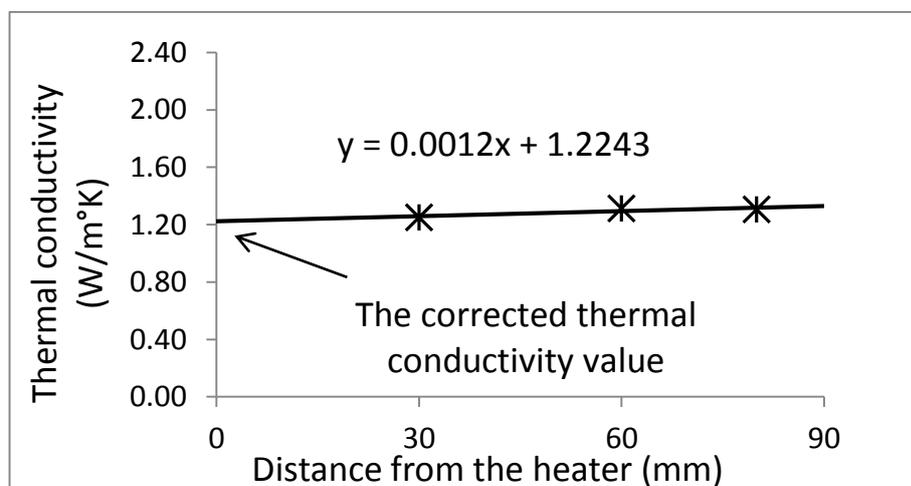


Figure 3-13 : An example of thermal conductivity correction method

3.4 Experimental assessment

The assessment of the thermal apparatus has been carried out by conducting a series of tests to evaluate the performance of the apparatus. In all tests, sand samples having the same water content and bulk density are used. The preparations of these samples and the test procedure have been described in section 3.3.2.2 (non-cohesive reconstituted samples). These tests are conducted to evaluate heat distribution in the specimens, the effect of thermocouple configuration, effect of sink disc temperature and the effect of the thermal jacket as well as to assess experimental error and repeatability.

3.4.1 Heat distribution in the specimen

To monitor the heat distribution along and across the specimens at steady state condition, the temperatures of twelve points for each specimen were measured after steady state condition has been reached. Six thermocouples (Figure 3-10), three from each side, are pushed toward the heater via small holes in the sink discs. The thermocouples are located one at the centre and the other two at 40 mm from the centre at the horizontal sides of the specimen. During the insertion of the thermocouples the temperatures are measured at distances of 90, 50, 10 and 00 mm from the heater. At each distance the thermocouples are kept for one hour to reach equilibrium and the average temperature of the last ten minutes is recorded.

3.4.2 Effect of thermocouples configuration

Since the thermal conductivity of the thermocouple material is very high compared with soil, it is important to test how significant are the effects of the number and the direction of the thermocouples on the soil thermal conductivity.

The first test was conducted to evaluate the effect of the number of the thermocouples. In this test, a thermal conductivity of a soil sample has been measured with different numbers of thermocouples. The test has been conducted using one mobile thermocouple for one sample and four fixed thermocouples for the other sample. At steady state condition, the temperature at distances 00, 30, 60, and 90mm are recorded for both samples. At each distance, the mobile thermocouple is kept at least for three hours to reach equilibrium and the average temperatures of the last ten minutes are recorded. Three thermal conductivity

values are measured for each sample using the three different distances from the heater and the corresponding temperatures.

The second test was conducted to evaluate the effect of the directions of the thermocouples. The thermal conductivity of two identical specimens is measured using three longitudinal (parallel to the heat flow) thermocouples for one specimen and three radial (perpendicular to the heat flow) thermocouples for the other specimen. The thermocouples are inserted at distances 00, 30, 60, and 90mm from the heater. The temperatures recorded at these points at steady state condition are used to calculate the thermal conductivity at different intervals.

3.4.3 Effect of natural and forced convection on sink discs

The function of the sink discs is to hold the specimens and to remove any heat coming from the specimens. The difference in temperature between the specimens and the ambient is the main factor that influences the rate of the heat transfer through the sink discs to the ambient. The temperature of the sink discs during the test indicates the efficiency of removing the heat from the specimen. It has been observed that at low temperature gradient, the sink temperature almost remains the same as the ambient temperature which means any heat coming from the specimen can be removed efficiently by natural convection at low temperature gradient. To examine the effect of the forced convection applied on the sink discs at high temperature gradient, the thermal conductivity of a dry soil specimen has been measured first at natural convection state and then with air forced convection applied on the sink discs. The dry soil is chosen because its high thermal resistance produces a higher temperature gradient easily with low input power. At steady state condition the temperature of three points are recorded and used to calculate the three values of thermal conductivities. At this point and to signify the effect of forced convection on the thermal conductivity, two electric fans are used to apply forced air on the sink discs to produce forced convection condition. The test is allowed to reach the steady state again (10 hours) and the three values of thermal conductivities are recalculated using the new recorded temperatures.

3.4.4 Effect of thermal jacket

The function of the thermal jacket is to minimize radial heat losses and to maximise heat flow longitudinally. Some tests have been conducted to assess and analyse the effect of the thermal jacket temperature on the calculated thermal conductivity. Also, these tests have been conducted to identify the ideal temperature level of the thermal jacket that is required to eliminate the radial heat losses. Three tests were required for this purpose. The first test was conducted to measure the thermal conductivity of a soil sample with thermal jacket temperature being maintained near ambient temperature. The second test was to continue the first test but with the thermal jacket temperature near average sample temperature. This has been done by raising the water bath temperature to the desired level. Finally, after completion of the second test the thermal jacketed temperature has been raised to near maximum sample temperature. To ensure that the steady condition has been reached at all stages, 24 hours were used as a testing period for each test. At each test, after the steady state has been reached the temperature of the three points were recorded and the thermal conductivities corresponding to these values were calculated. It is also important to mention that the temperature of water used to control the thermal jacket temperature should be a slightly higher than requires for the sample because of the cooling caused by the ambient temperature on the plastic tube that connects the thermal jacket to the water pump.

The thermal conductivities obtained from these tests were plotted against their corresponding lengths.

Using the temperature recorded at different points the amount of the radial heat flow q_{radial} can be calculated.

If T_0 , T_1 , and T_2 are the temperature at distances L_0 , L_1 , and L_2 from the heater respectively and q_1 and q_2 are the average longitudinal heat at the intervals $L_0 - L_1$ and $L_0 - L_2$ respectively, the amount of the radial loses q_{radial} between the two intervals can be valued as follows:

$$q_{radial} = q_1 - q_2 \quad 3.6$$

$$q_{radial} = q_1 \left(1 - \frac{L_1}{L_2} \cdot \frac{\Delta T_2}{\Delta T_1} \right) \quad 3.7$$

where $\Delta T_1 = T_0 - T_1$ and $\Delta T_2 = T_0 - T_2$

Accordingly, positive values of q_{radial} indicate the radial losses flow from the specimen to the thermal jacket and vice versa. The condition where no radial losses occur can be achieved when q_{radial} equals to zero.

To find out the ideal thermal jacket temperature where the slope is equal to zero, the temperature at two equal different intervals ($L_1=L_2=30\text{mm}$) has been measured at three levels of thermal jacket temperature. The relation between thermal jacket temperatures and the amount of the radial losses obtained from Eq. 3.8 can be used to detect the ideal thermal jacket temperature. In this test, the ambient temperature was 18.8°C , the average sample temperature was 27.7°C and the temperature of the thermal jacket where q_{radial} equals zero was 23.4°C .

3.4.5 Apparatus performance using reference material

The validation of the results has been checked by measuring the thermal conductivity of a well-documented reference material. Paraffin wax that has a thermal conductivity value of 0.25 W/m.K (The Engineering ToolBox, 2008) has been used at the beginning of testing program to calibrate the cell and verify the results. In this test, two specimens has been prepared by pouring the melted paraffin wax in a mould that has the same cross sectional area as the specimen cylinder (103 mm). The two specimens should have the same length and parallel faces.

3.4.6 Repeatability and error estimation

The uncertainty of the parameters used to determine the thermal conductivity will contribute to the overall result. These parameters are power q in W , temperature gradient ΔT in $^\circ\text{C}$, cross-sectional area in m^2 and specimen length in m . Also, the asymmetry that may exist during the preparation of the two specimens can be one of the sources of the uncertainty. To evaluate the margin of error caused by the uncertainty in these parameters, a fine sand sample has been tested several times under same conditions and the results are statistically analysed.

3.4.7 Comparison with transient probe method

Since the measurement of the thermal conductivity of porous material (soil) using steady state and transient state methods is still a controversial issue regarding the accuracy and the applications, the thermal conductivity of a sandy soil sample has been measured using the new steady state apparatus and using a transient method (Single probe method) under different conditions. It should be noted that there is no standard laboratory test to measure the thermal conductivity of soil using steady state methods while the transient state methods has been standardized. ASTM D 5334, 2008 is an example of standard transient test for measuring thermal conductivity of soil. Section 3.3 explains the sample preparation and the test procedure that are followed in the testing of sandy sample using the steady state new apparatus. The transient apparatus used to measure the thermal conductivity of the same sandy sample is a commercial thermal properties analyser, KD2 (Decagon Devices Inc). Figure 3-14 presents the set-up of the thermal conductivity measurement and the specification of the KD2 instrument.

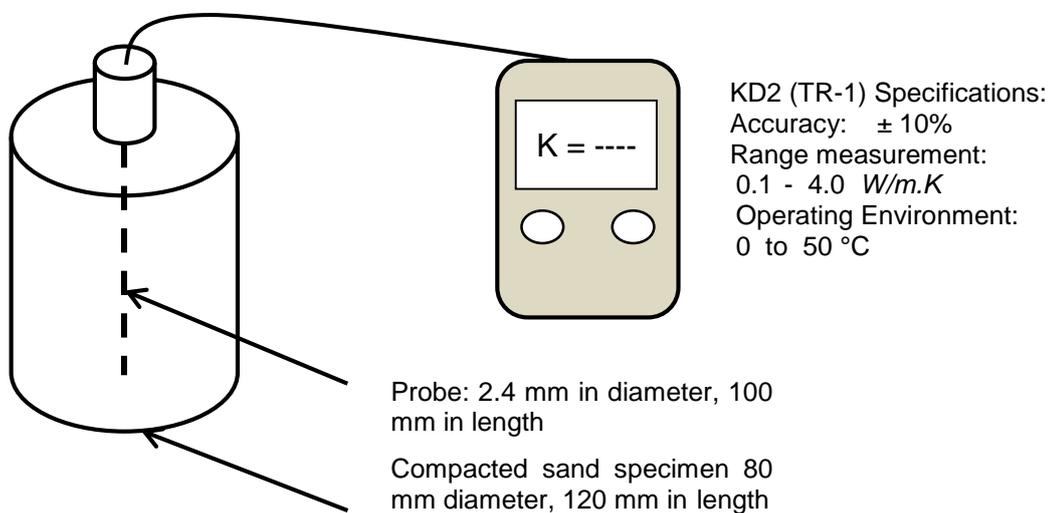


Figure 3-14 : Thermal conductivity using single probe method (KD2)

Its theory is based on the hot wire method where the thermal conductivity can be determined by monitoring the heat dissipation from a linear heat source (needle probe) having a large length to diameter ratio to simulate condition for an infinity

long (ASTM D 5334, 2008). The probe consists of a heating element (100 mm long and 2.4 mm in diameter) and a thermistor in the middle of the heating element. After inserting the probe into the soil sample (120 mm length and 80 mm in diameter), a known current and voltage are applied to the probe and the temperature rise with time is recorded over a period of time. The thermal conductivity of each sample is measured using 2.0, 5.0 and 10.0 minutes duration time.

3.5 Experimental results and discussion

3.5.1 Heat uniformity

The first test carried out in this study was conducted to monitor the heat distribution along and across the soil specimen at steady state condition. The profile of the heat can give a warning of any asymmetry of the parts comprising the cell body that may happen during the manufacturing process. The test involved the temperature measurement of twelve points for each specimen after steady state condition has been reached (three lateral points at distances 00, 30, 50, 90 mm from the heater).

Laterally, Figure 3-15 shows the temperature profile of three lateral points across the specimen.

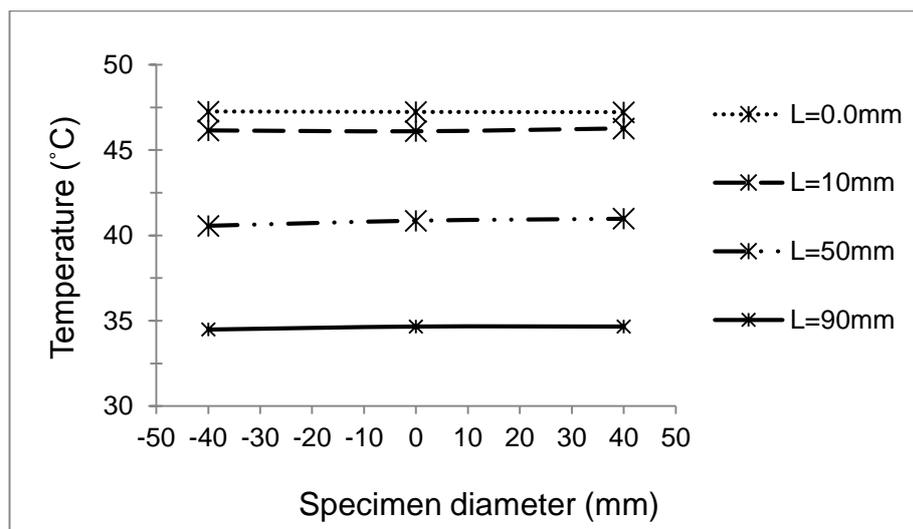


Figure 3-15 : Temperature profile of three lateral points

The horizontal lines connecting each three points indicate that the temperature is uniform at that particular cross section. This means the temperature near the

surface of the specimen is the same as that at the centre. One advantage can be concluded from this observation that it is possible to insert the thermocouples to any point along the diameter of the specimen without any significant error. However, it is accurate to insert all the thermocouples to the same distance from the centre of the specimen.

Longitudinally, Figure 3-16 shows the temperature profile along the specimen length.

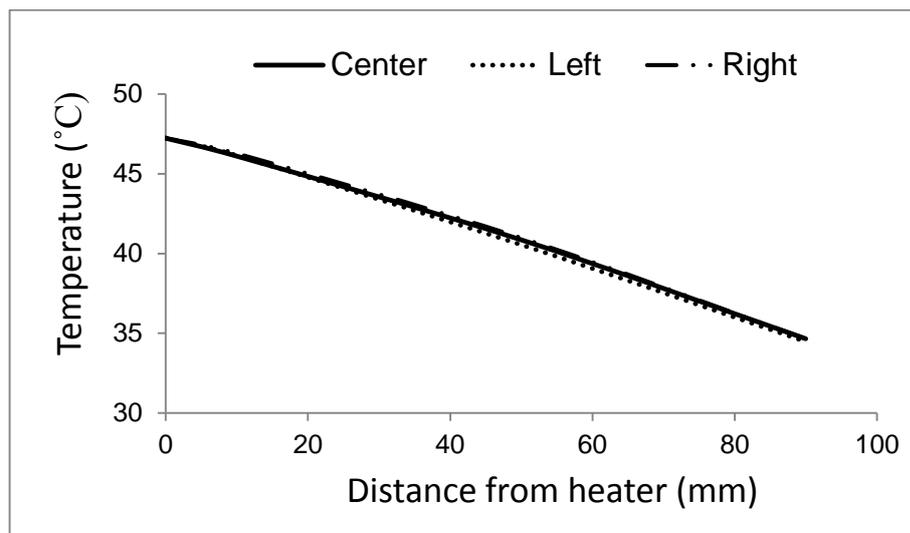


Figure 3-16 : Temperature profile along the specimen length

From this graph it is clear that the temperature gradients along the three longitudinal sections are approximately identical. The linearity of these gradients indicates that the rate of radial loss is constant along the specimen length. However, this linearity can be also attributed to the high difference in temperature between the specimen and the ambient. It is also remarkable that there are very slight differences between some analogous points which can be explained due to the non-homogeneity of the specimens.

3.5.2 Heat flow analysis

The new thermal cell was designed to produce unidirectional heat flow to enable Fourier's law to be applied reliably. Particularly, it is difficult to establish this condition due to the effect of the ambient temperature interface (ATI). The effect of the ambient temperature on the longitudinal and radial heat flow is essential. The common method to minimize the effect of ambient temperature is to use

insulation layer, keeping the ambient temperature constant and controlling the temperature of sink disk. The sink disk temperature can be in three levels. The first option is to keep the sink temperature higher than the ambient temperature which will produce a contrived heat flow from the sink into the specimen. The second option is to keep the sink temperature below the ambient temperature. This will make the outer portion of the specimen cooler which will give more chance of heat to inject radially from the ambient into the specimen. The best option is to keep the sink temperature near the ambient temperature however the radial losses will be linked to the efficiency of the insulation. In fact, to establish unidirectional heat flow, it is required to have a mechanism that separates and controls the two kinds of the heat flow (longitudinal and radial heat flow).

The new concept introduced in this work is the application of the thermal jacket. The function of the thermal jacket is to minimize radial heat losses and to maximise heat flow longitudinally. The thermal jacket was designed to produce a thermal gradient along the specimen length. However, due to the short length of the specimen, the heat equilibrium will take place between the three heat sources (specimen, thermal jacket and the heat from the ambient). The heat equilibrium will take place laterally as well as longitudinally until the steady state condition reached. As a result, the temperature gradient at the outer surface of the cell cylinder will be very low.

To assess and analyse the effect of the thermal jacket temperature on the calculated thermal conductivity and in order to identify the ideal temperature level which is required to eliminate the radial heat losses, the thermal conductivity was measured with thermal jacket temperature near ambient temperature, then at thermal jacket temperature near the average sample temperature and finally at a temperature near the maximum sample temperature. Figure 3-17 shows the effect of the thermal jacket temperature on the calculated thermal conductivities. The level of the thermal jacket temperature controls the amount and the direction of the radial heat flow along the specimen length. It can be observed that, when the temperature of the thermal jacket is kept below the average specimen temperature, the calculated thermal conductivity increases as the length of the specimen increases (the line with positive slope in Figure 3-17).

The increase of the thermal conductivity can be attributed to the following: in the calculations, the amount of heat is considered to be constant along the length of the specimen and equal to the input heat power (this is an ideal condition and can be achieved only if there are no radial losses). In fact, due to the presence of the radial losses the recorded temperatures at different positions are not caused by the same input heat power and the input heat power should be decreased in the calculations as the distance from the heater increases. Moreover, since the thermal jacket temperature is constant while the temperature of the specimen decreases along the specimen length, the temperature difference between the thermal jacket and the specimen decreases as the length of the specimen increases. Consequently, the rate of the heat loss decreases as the specimen length increases. This reduction will increase the ratio ($L / \Delta T$) in the Fourier's heat conduction equation without decreasing of the corresponding input heat power which results in increasing the calculated thermal conductivity.

Using the thermal jacket with temperature higher than maximum specimen temperature will reverse the phenomenon (the line with negative slope in Figure 3-17). In other words, the rate of the heat injected into the specimen (negative radial losses) will increase as the specimen length increases because of the increase of the difference in temperature between the thermal jacket and the specimen along the length of the specimen.

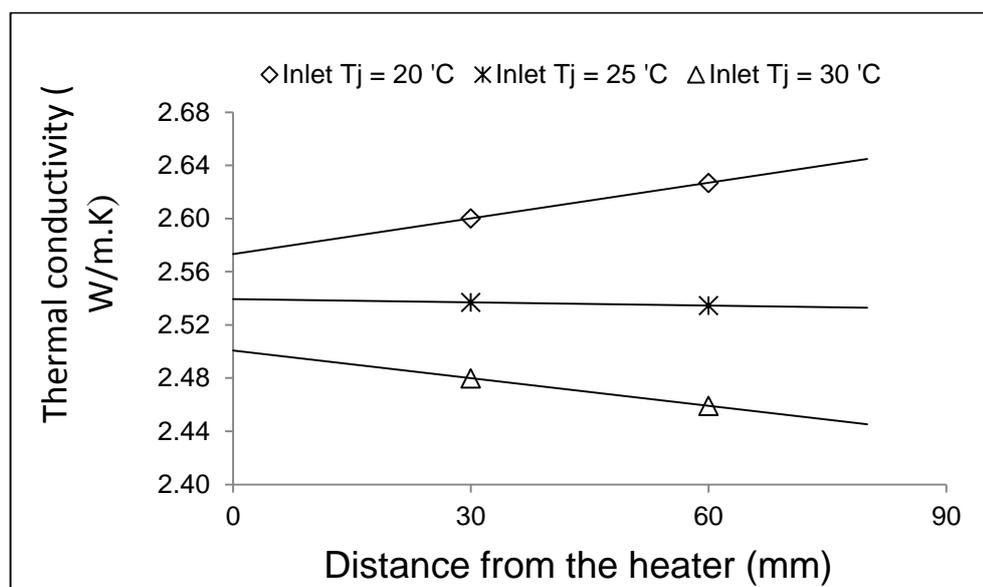


Figure 3-17 : Effect of thermal jacket temperature

3.5.3 Thermocouple configuration

Another important factor that can influence the heat flow is the thermocouple material. Since the thermal conductivity of the thermocouple material is much higher than soil, it is important to test how significant are the effect of the number and the direction of the thermocouples on the obtained results for the thermal conductivity.

Figure 3-18 shows the differences in thermal conductivity measured at distances 30, 60, and 90mm using one mobile thermocouple for one side and three fixed thermocouples for the other side. The result indicates that the thermal conductivity value measured using three thermocouples (2.467 $W/m.K$) is higher than using one mobile thermocouple (2.348 $W/m.K$). This difference (about 5%) highlights the importance of minimizing the number of the thermocouples, especially for soils with low thermal conductivity.

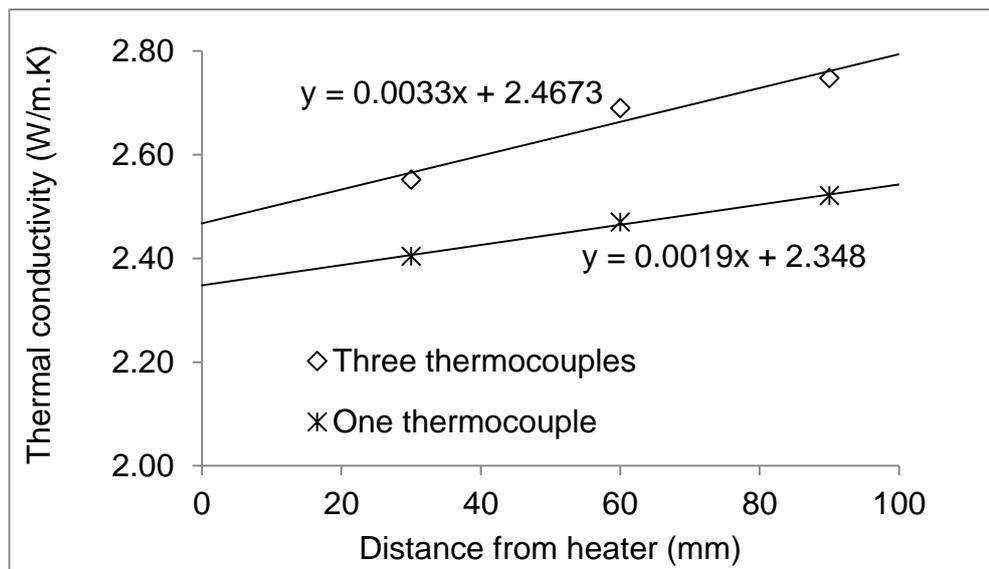


Figure 3-18 : Thermal conductivity measured using one mobile thermocouple and three fixed thermocouples

To signify the effect of the direction of the thermocouples, Figure 3-19 shows the results obtained using three longitudinal (parallel to the heat flow) thermocouples for one specimen and three radial (perpendicular to the heat flow) thermocouples for the other specimen. The result shows that, the determined thermal conductivity using thermocouples perpendicular to the heat flow direction (2.287 $W/m.K$) is much lower than using thermocouples parallel to the heat flow direction (2.707 $W/m.K$) with difference of 18.37%. This can be explained due to

additional heat flow caused by the thermocouple material when used parallel to heat flow direction.

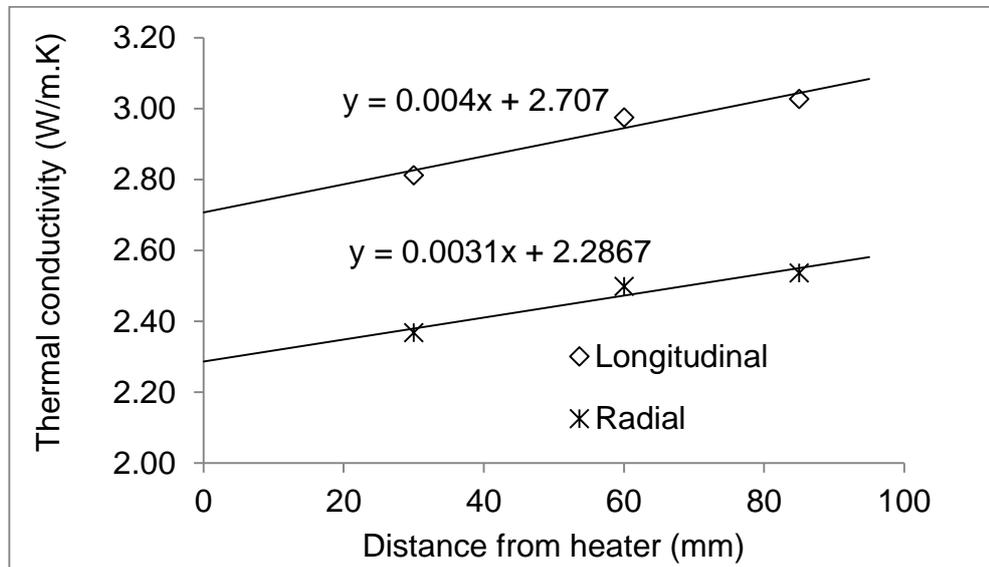


Figure 3-19 : Thermal conductivity measured using longitudinal and lateral thermocouples

3.5.4 Ideal thermal jacket temperature

In any experimental test, the slope of the line connecting the thermal conductivities at various intervals can be used to quantify the amount and the direction of radial heat loss along the specimen length. A positive slope indicates radial heat flows from the specimen into the ambient, and a negative slope indicates radial heat enters the specimen (Figure 3-17). Therefore, it is clear that there is a place where the balance condition can be established and no radial flow occurs. This condition can be detected when the calculated thermal conductivities are equal at any different intervals (ΔL) along the axes of the specimen (the line with horizontal trend in Figure 3-17). In other words, $\Delta L/\Delta T$ in Fourier's conduction equation is constant using any different intervals.

Equation 3.8 can be used to quantify the amount of the radial losses. To apply this equation it is only required to measure the temperature at three different points along the specimen length. From this equation, positive values of q_{radial} indicate the radial heat flow from the specimen to the thermal jacket and vice versa. The condition where no radial losses occur can be achieved when q_{radial}

equals to zero. Applying this equation at different levels of thermal jacket temperature has been used to detect the balanced condition. The relation between the thermal jacket temperature and the amount of the radial losses obtained from equation 3.8 has been plotted in Figure 3-20.

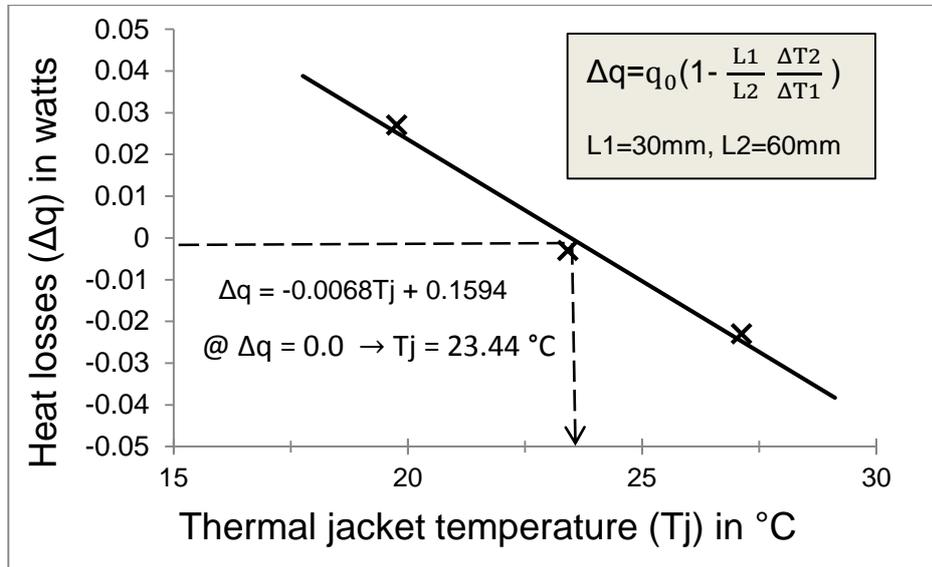


Figure 3-20 : Detection of ideal thermal jacket temperature

This relation reveals that the ideal thermal jacket temperature where q_{radial} equals zero is 23.4°C. In this test, the ambient temperature was 18.8°C and the average sample temperature was 27.7°C. As a result, the ideal thermal jacket temperature is approximately equal to the average value of the ambient temperature and average sample temperature.

The necessity of using the thermal jacket mainly depends on the temperature gradient along the specimen length as well as the difference in temperature between the ambient and the specimen. As these two parameters are kept very low, the effect of the thermal jacket can be insignificant. In contrast, a high gradient will increase the amount of the radial losses, and the rate of the radial losses will vary significantly along the length of the specimen. In this case, the thermal jacket can minimize the radial losses as it works as a heat barrier. However, in all cases using a thermal jacket with temperature near the minimum specimen temperature will be optimum.

3.5.5 Sink disc temperature

Aluminum was selected as the material for the sink discs because of its high thermal conductivity and diffusivity relative to soils. This would insure that the temperature was uniformly distributed across the ends of the specimens. The main function of the sink discs is to hold the specimens and to remove any heat coming from the specimens. It is important to insure that all the heat coming from the specimen is dissipated and not accumulated at the outer portion of the specimen. As explained in section 3.5.2, the best option is to keep the sink temperature near the ambient temperature. The difference in temperature between the specimens and the ambient is the main factor that influences the rate of the heat transfer from the specimen through the sink discs to the ambient. To ensure that the heat is dissipated efficiently by natural convection that occurs between the sink discs and the ambient, the thermal conductivity of a soil specimen was measured at natural convection state and compared with the results of the same soil specimen when air forced convection is applied on the sink discs. The temperature profiles along the specimen length of the two cases and the corresponding thermal conductivities are shown in Figure 3-21 and Figure 3-22 respectively. It can be observed that the calculated thermal conductivity for the two cases was almost the same with difference less than 1%. Therefore, the effect of forced convection can be considered insignificant and can be neglected especially for low temperature gradients.

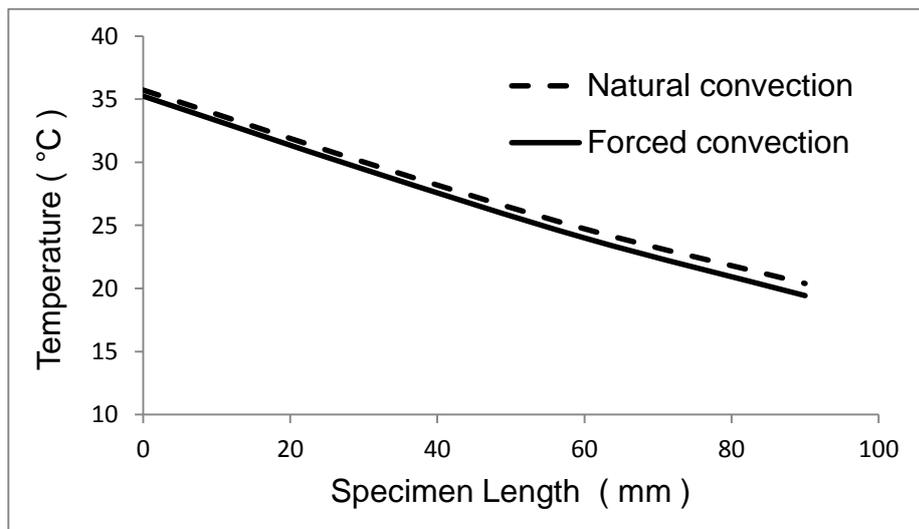


Figure 3-21 : Effect of forced convection on temperature profile

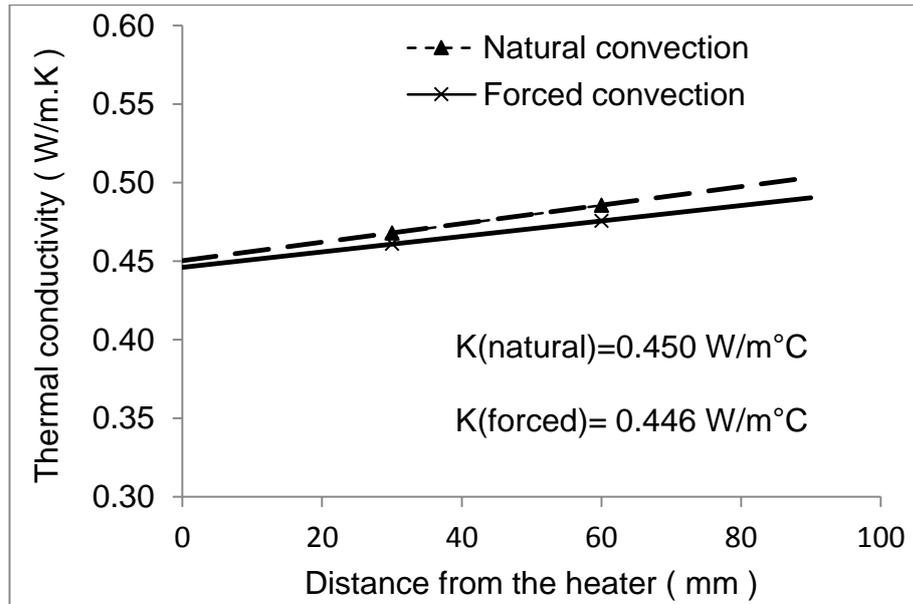


Figure 3-22 : Effect of forced convection on thermal conductivity

3.5.6 Apparatus performance using a reference material

The adequacy of the new apparatus in measuring thermal conductivity of soils has been checked by measuring the thermal conductivity of paraffin wax that has a value of 0.25 W/m.K as documented by Engineering Toolbox (The Engineering ToolBox, 2008). The measured value was 0.29 W/m.K , which is 15.6% greater than the specified value. This outcome was expected as the documented value is based on the transient method and the two methods give systematically different results in measuring thermal conductivity of soils (Midttomme and Roaldset, 1999; Abuel-Naga et al., 2009). Furthermore, when some national measurement organizations carried out a measurement program of some available reference materials to be used internationally, the results show that there is laboratory-to-laboratory difference for each material (Salmon, 2001). For this reasons any results obtained using steady state methods is likely to have different values when compared with documented results. Therefore, the performance of any apparatus used to estimate the thermal conductivity of soils under steady state methods can be evaluated by the accuracy of controlling the boundary conditions to ensure that the parameters used in calculations are realistic.

The uncertainty of the parameters used to determine the thermal conductivity will contribute to the overall result. These parameters are power q in W , temperature gradient ΔT in $^{\circ}C$, cross-sectional area A in m^2 and specimen length L in m . To evaluate the margin of error caused by the uncertainty in these parameters, a fine sand sample has been tested several times under the same conditions. The results of these tests are shown in Figure 3-23.

The average value of the thermal conductivity was $1.720 W/m.K$ and the standard error was 5.07% of the average value which equals to $0.068 W/m.K$. The thermal conductivity value has an uncertainty equal to the standard error estimated from the results. Therefore, the thermal conductivity of this sample can be given as $1.720 \pm 0.068 W/m.K$.

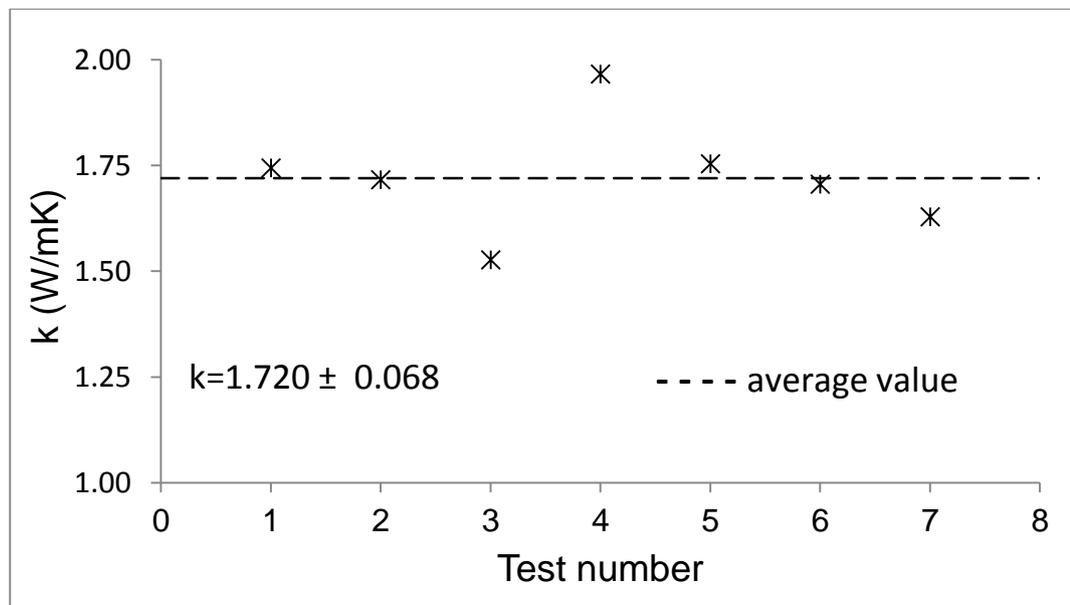


Figure 3-23 : Repeatability of results for fine sand sample

3.5.7 Comparison with transient method

The thermal conductivity of sandy soil specimens have been measured using the new apparatus and KD2 probe at four degrees of saturation. At each degree of saturation, the thermal conductivity is measured at four different dry densities. Figure 3-24 a-d presents the results obtained from these tests.

From these results, the first important observation is that at dry condition the thermal conductivity measured using the new apparatus is approximately twice

that measured using the KD2 at all dry densities. The lower thermal conductivity results obtained using the probe method can be attributed to the high contact resistance that occurs between the probe and the dry soil. Also, the large diameter of the probe can be another cause of this reduction where departure from the assumption of an infinitely thin probe causes potential significant differences in estimation of the thermal conductivity due to non-negligible heat storage and transmission in needle probe itself (ASTM D 5334 – 2008). In contrast, at saturated condition the thermal conductivity values measured using both methods are approximately identical except at very low dry density. This can be explained as the pore space is completely filled with water and the contact resistance between the probe and the soil is eliminated. At partially saturated conditions the relative difference between the results obtained by the two methods gradually decreases as the saturation increases and the dry density decreases.

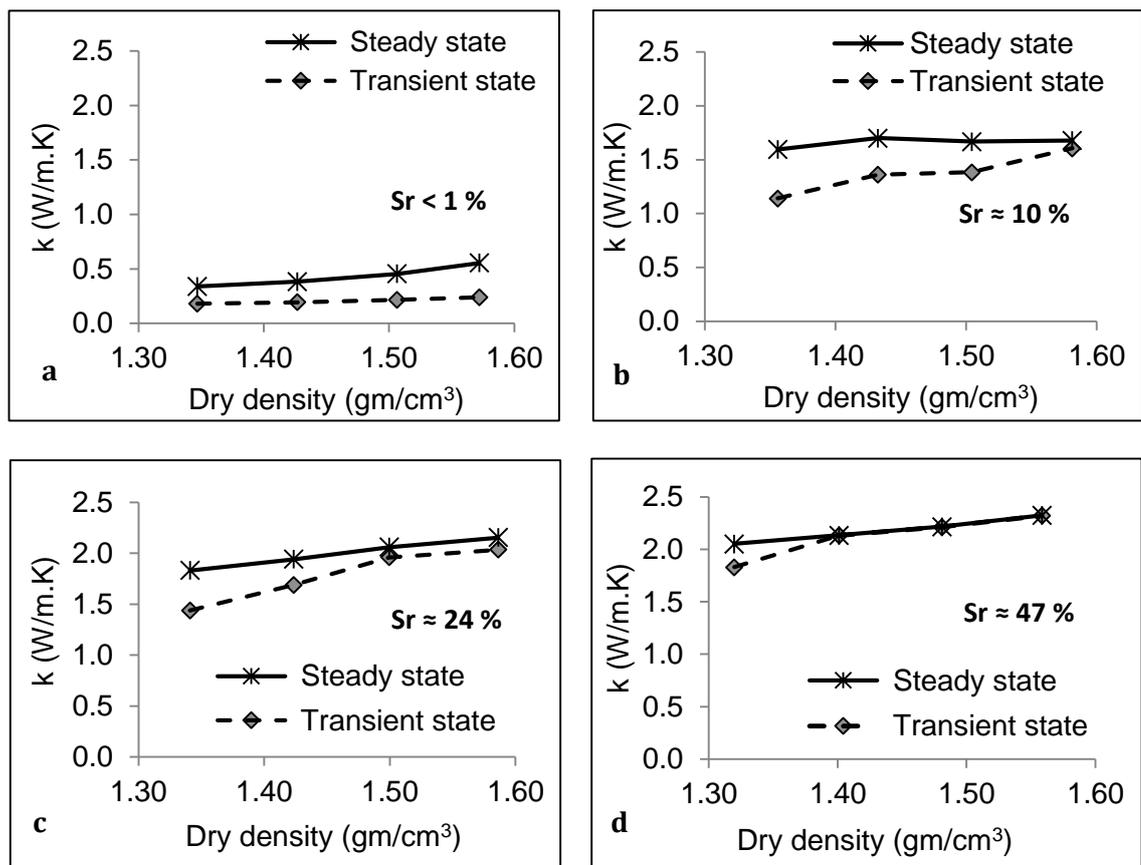


Figure 3-24 : Thermal conductivity results obtained using steady and transient state methods at different conditions

The differences in the results obtained by the two methods in measuring thermal conductivity of soils have been reported by many researchers. In some studies, the deviation reached 50% between the methods however the average discrepancy between them is in the range of 10-20% (Midttomme and Roaldset, 1999; Abuel-Naga et al., 2009). In this research the average discrepancy was 18 % however at dry condition it is more than 50 % and at saturated high density conditions a neglected discrepancy is observed.

It is also remarkable that the effect of the dry density on the thermal conductivity is insignificant compared to the effect of the degree of saturation. Therefore, if the effect of the dry density is neglected and the average value of thermal conductivity at each level of saturation is considered, Figure 3-25 clarifies that the relative difference in the thermal conductivity results obtained by the two methods become closer as the degree of saturation increases. Therefore, the two methods can be used, without major error, only at high degrees of saturation. In other words, if 10 % is considered as an acceptable difference value then the two methods can be applied only at saturations above 25 %.

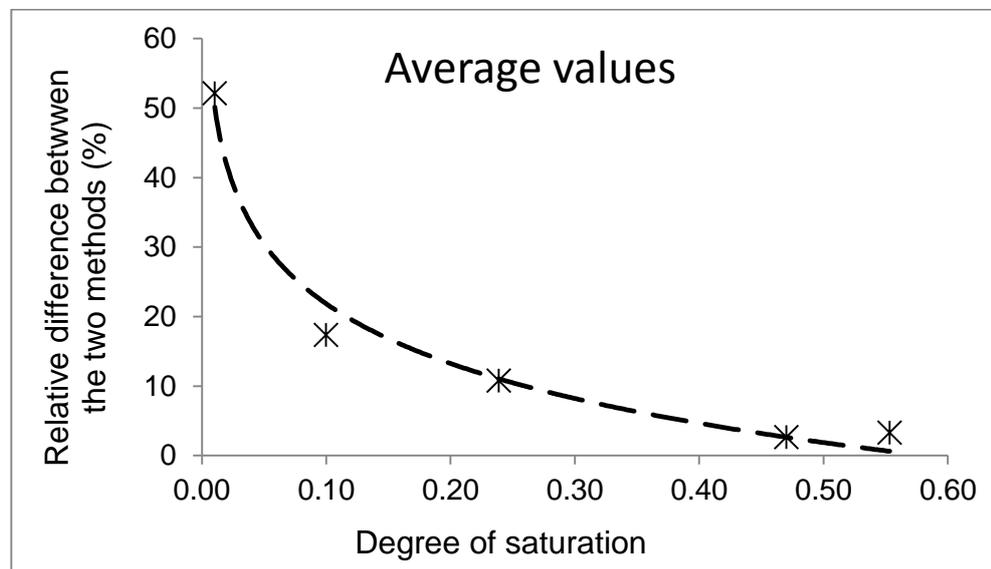


Figure 3-25 : Relative difference in the thermal conductivity values obtained by the new steady state apparatus and the probe method

Regarding the probe method, it has been observed that different results have been obtained at different test time durations (2.0, 5.0 and 10.0 minutes), Figure

3-26 is an example of this remark. Using a short time is preferable to minimize the moisture migration however long heating time can minimize the contact resistance. The average values are considered to be acceptable.

From the above discussion, it can be concluded that the results obtained by the steady state divided bar method (the new apparatus) at dry conditions can be considered more accurate than that obtained by probe method. This is because there is no concern of moisture migration at dry condition, which is one of the disadvantages of the steady state methods, while the contact resistance in the probe methods is in a major concern. At partially saturated condition both methods have the possibility of moisture migration however contact resistance in probe methods still can be a point of concern. At saturation conditions, the contact resistance in probe methods is eliminated and the values obtained by the KD2 can be considered as accurate results. The results obtained by the new steady state apparatus are similar. This indicates that the factors influencing the thermal conductivity measurement using the new apparatus, mainly the radial losses caused by the ambient temperature interface (ATI), are well controlled.

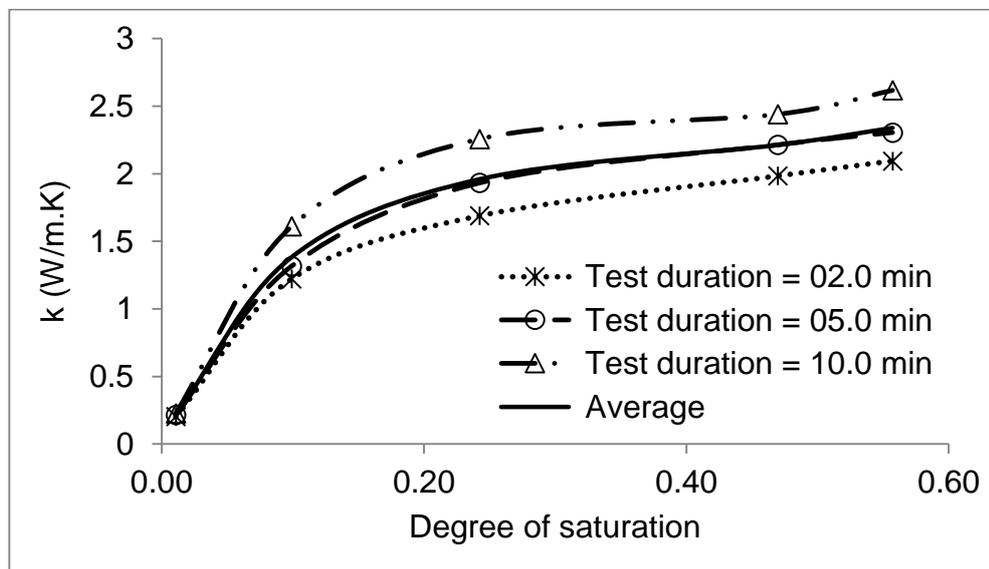


Figure 3-26 : KD2 results using different test durations

3.6 Practical application

As a part of its testing and to recognize any unforeseen complications, the new apparatus was used to measure the thermal conductivity of undisturbed and reconstituted cohesive samples. For non-cohesive soils the use of the new apparatus will be illustrated in Chapter 5 as it focuses on the thermal conductivity measurements of sandy soil.

3.6.1 Testing of undisturbed samples

The new apparatus was used to measure the thermal conductivity of undisturbed glacial till samples. Glacial till is a drift deposit covering much of northern England and Scotland and is typically found as a stiff, un-stratified clay, often containing laminations, or lenses, of sand and gravel. Three U100 samples extracted from different depths in boreholes near Newcastle were tested. Two identical specimens were prepared from each sample (Figure 3-27).

During preparation, it was noted that each sample has different constituents which include small and large pieces of gravel.

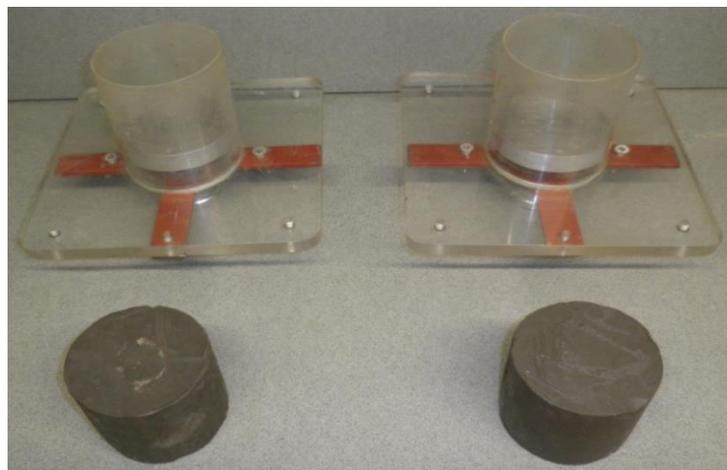


Figure 3-27 : Undisturbed glacial till samples prepared for testing

The thermal conductivity of each two identical specimens was measured according to the procedure mentioned previously. The initial water content of each specimen was determined. Table 3-1 shows the physical properties and the measured thermal conductivities of the three samples.

Sample	Water content	Porosity	Degree of saturation	Bulk density	Dry density	Thermal conductivity
	%	%	%	g/cm ³	g/cm ³	W/m.K
Undisturbed, Cohesive (Glacial Till)	32.2	53.77	74.73	1.840	1.248	1.308
	31.6	50.93	82.22	1.911	1.325	1.125
	21.6	42.82	77.89	1.970	1.544	1.943
Reconstituted, Cohesive (Glacial Till)	21.1	41.85	79.15	1.990	1.570	1.221
	25.4	46.93	77.57	1.919	1.433	1.385

Table 3-1 : Results of testing of undisturbed and reconstituted glacial till samples

The high thermal conductivity of the third sample can be explained due to the high amount of gravel fragments. It can be noted that the comparison of these values with any reported results is questionable because each sample has its individual characteristics. However, the results can be considered within the expected range of the thermal conductivity values for glacial till soils in UK which ranges from 0.9 to 2.3 *W/m.K* (Busby et al., 2009).

3.6.2 Testing of cohesive soils

The disturbed portions of the U100 samples that were previously tested as undisturbed samples were remoulded and retested. Two tests have been carried out. For each test, two specimens were prepared with removal of gravel fragments, mixing with water to make a semi-liquid slurry, consolidation of the slurry using a consolidation cell having the same cross-sectional area as the specimen cylinder (this can take several days), and then cutting the specimen to the desired length. The thermal conductivity results of these tests are shown in Table 3-1. The existence of small particles of gravel and the variation in moisture content as well as dry density can explain the slight differences in the obtained results.

3.7 Summary

Measurement of thermal conductivity of soils is crucial for the design of thermogeology energy systems. New laboratory equipment has been designed for this purpose. The design is based on the application of Fourier's law of one-dimensional heat conduction at steady state condition. In addition to its simplicity, the new cell can be used for field samples (U100 samples) as well as laboratory-prepared specimens. Each part of the cell was designed appropriately to optimize the performance of the apparatus. All the factors affecting and controlling the design have been described. The main factor influencing the measurement is the radial heat losses that occur due to the ambient temperature interface (ATI). A new concept of minimizing the radial heat losses using a thermal jacket as a heat insulation barrier was proposed. A detailed description of the thermal cell parts as well as the instrumentation required to complete the thermal test were presented in this chapter. As this apparatus was designed to cover different soil conditions, the preparation of soil specimens was also described. This includes the preparation of undisturbed field samples as well as cohesive and non-cohesive laboratory prepared samples. The test set-up and procedure followed by calculations and correction method were explained as a final step to obtain the required data for determining the thermal conductivity of the tested specimen. The evaluation of the performance of the new apparatus has been explained in detail through the experimental assessment section. This section included all the experimental tests that are required to test the effect of each individual parameter such as thermal jacket temperature, forced convection and thermocouple direction on the obtained results. It also included verification results by testing well-known material and compared the results with documented value. A comparison between the new steady state apparatus and transient probe method (KD2) is presented throughout an experimental testing of sandy samples to value the difference between them. The final part of this section related to the error estimation and the uncertainty of the parameters used in this test that may contribute the final thermal conductivity result.

The discussion of the experimental tests that have been carried out to evaluate the performance of the new thermal cell showed a high degree of control of all operating variables. Moreover, the analysis of the heat distribution and the heat

flow revealed that the longitudinal heat flow can be maximized and the radial heat flow can be minimized when the thermal jacket is used with proper temperature level. The comparison between the results obtained using the new apparatus and probe method showed that the two methods can be used effectively at high degrees of saturation especially at dense conditions. Also, the discussion showed that the new apparatus can be considered more accurate than the probe method in measuring thermal conductivity of soils. Accordingly, the obtained results can be considered more confident and realistic which can help to standardize the measurements of the thermal conductivity of soils using the steady state technique.

Finally, the new apparatus was used to measure the thermal conductivity of undisturbed and reconstituted cohesive samples. These tests have been carried out as a practical application to recognize any unforeseen complications that may occur during the test period. The sample preparation and the test procedure for the two different soil conditions highlighted the simplicity of using the new apparatus in measurement of the thermal conductivity of soils.

Chapter 4 : Thermal enhancement of PFA-based grout for borehole heat exchangers.

4.1 Introduction

As the demand for cleaner, cheaper and sustainable energy sources is increasing, ground-source heat pump (GSHP) systems are receiving growing attention. The output of energy emanating from the Earth's crust to the surface is equivalent to 40TW (Mc Corry et al., 2011). Utilization of this energy is dependent on the type of GSHP application. The vertical closed loop system is favoured for any type of geology as compared to other methods.

GSHP technology harnesses the heat stored at shallow depth in soil and near-surface rocks for the heating and cooling of the buildings. The GSHP system is a new technology that gives high assurance as an efficient and cheap method of heating / cooling as compared to air source heat pump, gas boilers, radiators etc. This is consequent upon the fact that heating and air conditioning systems are currently regarded as one of the most energy consuming devices (Ben Jmaa Derbel and Kanoun, 2010). Overall efficiencies for GSHP systems are essentially higher than for air source heat pumps, because ground temperatures are higher than the mean air temperature in winter and lower in summer. The ground temperature also remains relatively stable, allowing the heat pump to operate close to its optimal design point. On the other hand, Air has a lower specific heat capacity than water, so to supply the same energy more air must be supplied to the heat pump, which in turn requires more energy. Comparing the heating systems regarding to seasonal efficiency, which is defined as the ratio of the energy delivered from the heat pump to the total energy supplied to it, the well-designed GSHP systems provide seasonal efficiencies of between 300 and 400 per cent and air source heat pump systems is about 250 per cent while the best gas boilers can provide less than 100 per cent (Energy Saving Trust, 2007). It was stated by British Geological Survey in the report of Gale (2005) that heating

with the aid of GSHP reduces the amount of energy required roughly by 70% compared with electric heating.

The design (number and depth of boreholes) of a GSHP system is much reliant on the thermal properties of the ground as well as the thermal conductivity of grout used as a backfill for a closed loop GHSP system (Witte et al., 2002; Hwang et al., 2010). In a closed-loop vertical heat exchanger, one of the most important factors that influence the efficiency of the system is the thermal resistance of the borehole which is directly connected to the thermal properties of the backfill material. For greater heat yield to the heat pump, the grout must be of a higher thermal conductive material. In contrast, grouts with low thermal conductivity will yield poor performance. From an economic point of view, previous research work proved considerable reduction in the borehole length of GSHP when an improved thermal grout was tested (Allan and Philippacopoulos, 1998). This could also reduce the number of boreholes required for a GSHP vertical loop system and cumulatively result in substantial cost savings in the total cost of installation.

The conventional grout in use is mainly bentonite based. However, bentonite-based grout has relatively low thermal conductivity and susceptible to shrinkage and cracking due to moisture losses. This has led to new research to develop varieties of grouts with higher conductance, such as cement-based grouts. There are other materials that have been used for grouting applications, such as Pulverised Fuel Ash (PFA). This is because PFA has good rheological properties such as workability, permeability and low shrinkage and also is relatively abundant. PFA grout is a blend of suspensions of PFA, Portland cement and water. However, this type of grout has not been used much as a thermal grout.

PFA has been used for several years since the 1950's for variety of applications (UKQAA, 2006). PFA is considered as a waste material in that its disposal has serious restrictions by legislation. It has been used from the onset as an alternative to sand and cement grouts because of the technical, rheological, durability and economic advantages it offers mostly in the construction industry to stabilize soils, earth filling, concrete works and manufacture of insulating block / bricks for building homes. PFA grouts, however, have low thermal insulation and PFA has been used for production of insulation blocks for buildings. There is a need to improve its thermal conductivity if it is to be used for GSHP by addition

of aggregate just as employed by Allan and Philippacopoulos (1998) and XU and Chung (2000). Environmentally, there is the need to diversify the use of PFA to other uses such as in thermal GSHP in order to remove roughly 300,000 tons of PFA and FBA (furnace bottom ash) from land fill per year (UKQAA, 2006). Also, there is lack of sufficient data for PFA thermal grout for researchers. All these prompted this research work.

The purpose of this work is to produce a thermal grout that can be used as a backfill material in borehole heat exchangers using unwanted industrial and domestic materials (PFA and ground glass) with relatively high thermal conductivity and that is economically effective. The target in this work is to enhance the thermal conductivity of PFA-based grout by adding some solid materials with relatively high thermal conductivity such as silica sand and/or fluorspar. This work when achieved will not only cut down installation cost of GSHP, but will tend to open up the use of PFA and the ground glass for more useful things than it were applied before.

4.2 Material

The grouts for this work comprise pulverised fuel ash blended with cement, ground glass, coarse sand, fine sand or fluorspar in different mix proportions. Table 4-1 presents mineralogical compositions of these materials determined by X-ray fluorescence (XRF).

4.2.1 Pulverized Fuel Ash (PFA)

The PFA Figure 4-1 a was obtained from Longannett power station, Kincardine, Scotland. The specification of the PFA is in accordance with (BS EN 197-1, 2011). The texture of PFA is fine (powdered form) and comprises ash spheres with average particle density of 2.15 (UKQAA, 2006). The lower particle density of PFA can be an advantage compared with cement that is 3.12 and sand 2.70.

4.2.2 Cement

General purpose cement Figure 4-1 b that conforms the requirement of BS EN 197-1 (2011) was used in this work for economy and because it can be used for varied application in construction.

	Cement (%)	Ground glass (%)	Fine sand (%)	Fluorspar (%)	PFA (%)
SiO ₂	30.030	66.180	85.280	12.74	50.470
TiO ₂	00.472	00.067	00.179	00.005	01.067
Al ₂ O ₃	10.710	01.670	02.880	00.040	23.800
Fe ₂ O ₃	04.930	00.410	01.390	00.280	07.290
MnO	00.090	00.020	00.030	00.000	00.070
MgO	02.310	01.530	00.710	00.060	01.600
CaO	46.130	10.740	04.170	18.630	04.670
Na ₂ O	00.420	13.360	00.320	00.040	00.570
K ₂ O	00.920	00.720	01.300	00.000	01.460
P ₂ O ₅	00.220	00.010	00.070	00.020	00.980
SO ₃	02.357	00.088	00.007	00.107	00.449
Ca \cong F				33.510	
F				31.770	
Total	100.67	95.32	100.61	97.920	99.45

Table 4-1 : Compositions of materials used in this study, determined by X-ray fluorescence (Department of Geology, University of Leicester, UK).

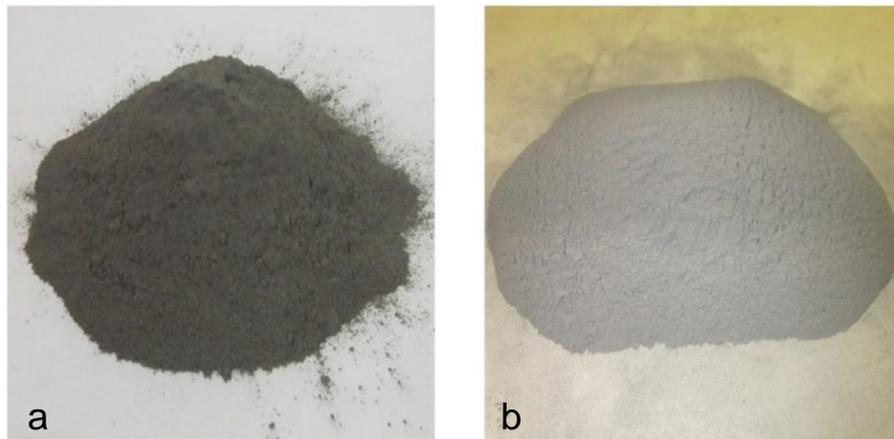


Figure 4-1 : (a) Pulverized Fuel Ash (PFA) (b) General purpose Portland cement

4.2.3 Ground Glass

The ground glass Figure 4-2 a-d was obtained from waste scrap glass and has been prepared locally in the laboratory. After thorough washing to get rid of dirt, it was dried in an oven for 24hrs. Thereafter, the glass was ground to a reasonable particle size and sieved through sieves of mesh sizes 2 mm, 1 mm, 0.6 mm and pan respectively. The particle sizes collected on 1mm and 0.6 mm mesh sizes were used as coarse and medium ground glass respectively. Coefficients of uniformity and curvature of the blended glass are 3.41 and 0.88 respectively.



Figure 4-2 : Ground glass: (a) Raw (b) Coarse size (c) Medium size (d) Fine size

4.2.4 Coarse Sand

The coarse sand Figure 4-3 a conforms to BS 1377- 4 (1990). It is clean and dry silica sand obtained from the Woburn beds of the Lower Greensand in the Leighton Buzzard, England, district, with grading of 100% passing a 600 μ m test sieve and 100% retained on 63 μ m test sieve. It does not contain foreign particles of any type including flaky particles, silt, clay and organic.

4.2.5 Fine Sand

Fine silver sand Figure 4-3 b was purchased from JT Dove, a local building materials merchant in Newcastle upon Tyne. The sieve analysis indicates that this sand can be classified as fine sand with coefficient of uniformity and curvature of 1.76 and 0.95 respectively.

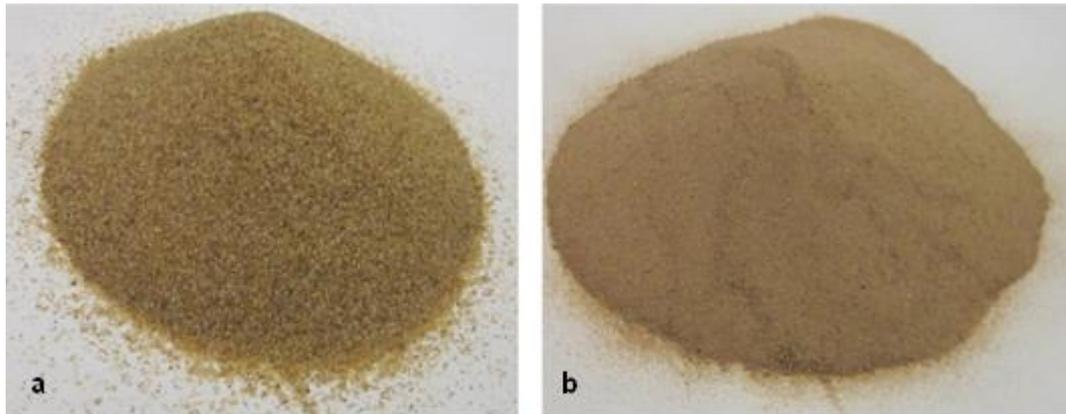


Figure 4-3 : (a) Course sand (b) Fine sand

4.2.6 Fluorspar

The fluorspar (fluorite plus quartz) was collected from Grove Rake Mine, Rookhope, UK. The material was not clean and came as large stones. The preparation of the fluorspar included breaking of the stones into small fragments, removal of the impurities such as rocks, followed by grinding to a reasonable particle size and sieving through sieves of mesh sizes 2mm, 1mm, 0.6mm and pan respectively (Figure 4-4).



Figure 4-4 : Fluorspar

4.3 Mix design

PFA grout is a blend of suspensions of PFA, Portland cement and water. For comparison, it was essential to know the thermal conductivity of the PFA grout without any added enhancement material. So, the first mix comprises only PFA and Portland cement which is referred as basic grout. However, it should be noted that the percentage of the cement used in this grout was slightly higher than other grouts due to the small particle size of the PFA which need more binder for bonding. Also, from an economic point of view, the amount of PFA used in each group was ensured to be higher than 20% by weight.

The materials listed in last section were suggested to enhance the thermal conductivity of the grout. Accordingly, the new grouts comprise of basic materials (PFA and cement) with one or more blends of enhancing materials.

To simplify the comparison between the grouts, the used amount of the binder (Portland cement) was considered to be at constant percentage in all mixes. However, it was assumed that the small variation in the percentage of the binder will not have significant effect on the thermal conductivity of the grout. For the simplicity of identification and analysis, the grouts were categorized into groups A, B, C, D, E, F and G. Each group involves at least three grouts having same constituents at different proportions. Table 4-2 shows the details of the designed groups.

Group	Mix	Cement	PFA	Coarse sand	Fine sand	Ground glass			Fluor spar
						Medium	Course	Mixed	
		% Wt.	% Wt.	% Wt.	% Wt.	% Wt.	% Wt.	% Wt.	% Wt.
A	A1	20	20	60	--	--	--	--	--
	A2	20	40	40	--	--	--	--	--
	A3	20	60	20	--	--	--	--	--
B	B1	20	20	--	60	--	--	--	--
	B2	20	40	--	40	--	--	--	--
	B3	20	60	--	20	--	--	--	--

C	C1	20	20	--	--	60	--	--	--
	C2	20	40	--	--	40	--	--	--
	C3	20	60	--	--	20	--	--	--
D	D1	20	20	--	--	--	60	--	--
	D2	20	40	--	--	--	40	--	--
	D3	20	60	--	--	--	20	--	--
E	E1	20	20	--	--	--	--	60	--
	E2	20	40	--	--	--	--	40	--
	E3	20	60	--	--	--	--	20	--
F	F1	20	20	--	--	--	--	--	60
	F2	20	30	--	--	--	--	--	50
	F3	20	40	--	--	--	--	--	40
	F4	20	50	--	--	--	--	--	30
G	G1	20	10	--	--	--	25	--	45
	G2	20	20	--	--	--	20	--	40
	G3	20	30	--	--	--	15	--	35
	G4	20	40	--	--	--	10	--	30

Table 4-2 : Details of suggested grout groups

4.4 Sample preparation

For each type of grout, the materials were batched by weight according to its mix proportion and then mixed in an electrically driven mixer. Firstly, the cementitious material (PFA and cement) were mixed with water to form slurry followed by addition of solid materials.

It is typical in mix design to identify the water/cementitious material ratio. However, in this case it was difficult to blend all the grouts using the same water/cementitious material ratio. This was due to the fact that grouts with more solid aggregate require less water to become pasty or to flow as compared to those with higher proportions of cementitious materials. That is, the desired water / cementitious material ratio that will make grouts with higher PFA flow will cause those grouts with higher proportions of solid aggregate turn to complete fluid and segregate. So care was taken in mixing the grouts until the required mix

consistency was achieved. Although, water / cementitious material should be minimized to avoid any access water that may cause bleeding, segregation and extra voids, the flow value for pumpability requirements was the main factor that controls this parameter. The pumpability can be improved without the need of more water in the grout mix. Plasticizers/super plasticizers are commonly used for this purpose. In this work since the PFA and ground glass will be used to design a new thermal grout and to predict the thermal conductivity in real form, no plasticizer or any other additives will be used.

According to the experimental programme four types of tests were required to perform. No samples were required to prepare for flow and the shrinkage tests as they were conducted immediately after successful mixing of each grout. For thermal conductivity measurements, two identical, cylindrical specimens with diameter of 103 mm and length of 90 mm were moulded. Another cylindrical specimen with same diameter and length of 148 mm was moulded for the preparation of permeability test. After 24 hours, the three specimens were water cured for at least 28 days (Figure 4-5).



Figure 4-5 : Water curing of grout specimens

The main purpose of the curing is to ensure that the chemical reactions (hydration) between the mix components are completed and the grout particles have reached its final state of bonding.

4.5 Experimental testing

The performance of the conventional boreholes, used as vertical ground heat exchangers, is significantly limited to the thermal conductivity of the backfill material. The aim of this work was to produce a thermal grout for the application of ground heat exchangers using unwanted materials. The main experimental work was focusing on the measurement of the thermal conductivity of the proposed grouts. However, in addition of the desired high thermal conductivity, the grout should fulfil the minimum requirements of some other parameters such as grout flow, shrinkage and permeability.

4.5.1 Grout flow

Following successful mixing, the grouts were tested for flow in accordance with BS EN 13395 (2002). The flow apparatus consists of the grout flow trough and the charging hopper (Figure 4-6). The surface of the grout flow trough was moistened with a damp cloth within one minute of carrying out the test. The sample of the grout was then poured into the charging hopper. The flow of the grout was measured as the horizontal distance from the centre of the discharge outlet to the end of the grout after 30 seconds started from the time of pulling up the pull-rod.



Figure 4-6 : Flow test apparatus

4.5.2 Shrinkage

The grouts were tested for linear shrinkage tests in accordance with BS 1377 - 1 (1990). Using shrinkage moulds, three grout specimens were moulded immediately after a successful mixing of each grout (Figure 4-7). After 24 hours, the grout specimens were removed carefully from the mould and the length of the each specimen was measured. After 27 days, the lengths of the specimens were again measured. The linear shrinkage was evaluated in mm/m as the mean of three values based on the initial measurement.



Figure 4-7 : Shrinkage measurement using brass moulds

4.5.3 Thermal conductivity

The thermal conductivities of the grouts were measured at saturated and dry conditions using the new thermal cell that utilizes steady-state methods in measuring thermal conductivity of soils. The design of the apparatus is based on the application of Fourier's law where a one-directional uniform heat flux is generated through two identical specimens. The details of the apparatus were explained in Chapter 3.

The thermal conductivity of the saturated specimens was measured firstly. Before starting the test the two saturated specimens were weighed for water content monitoring. The test procedure follows the same steps of the stiff field specimens as explained in Chapter Three. It is important to improve the thermal contact between the surface of the grout that are in direct contact with the sink and heater

discs. This can be achieved by applying a thin layer of thermal grease and exerting equal external pressure using the long steel studs. Also, it is important to keep the moisture content constant along the test period. This has been achieved by two steps: the first was by sealing the line contacts between the sink discs and the cylinders as well as the thermocouple's contact points. The second was by using as low a temperature gradient as possible. The calculation of the thermal conductivity and the correction step has been explained in Chapter Three. After the test was completed, the two specimens were reweighed and oven dried for 24 hours. Following the same procedure, the two specimens were retested as dry specimens after cooling down.

4.5.4 Permeability

The falling head test method was adopted for this work. Cylindrical samples of 103mm in diameter and 148 mm in height were casted, cured for 28 days (Figure 4-5) and conducted for falling head test based on BS 1377 - 5 (1990). Three tests were run per sample of grout and their average was used to calculate the coefficient of permeability (K) of the grouts based on Darcy's law as given below.

$$K = \frac{al}{At} \cdot \ln \frac{H_0}{H_1} \quad (m/sec) \quad 4.1$$

where: a is the area of burette, l is the length of grout sample, A is the cross sectional area of grout sample, H_0 is the initial head of water, H_1 is final head of water and t is the elapsed time during which head falls from H_0 to H_1 .

It should be noted that only specified grouts that have high thermal conductivity were tested as specimens with lower thermal conductivity were excluded as any more tests were justified.

4.6 Results and discussion

The prime purpose of this work was to increase the thermal conductivity of PFA-based grout for the use as a thermal grout for borehole heat exchangers.

4.6.1 Thermal conductivity results

After 28 days of curing, the thermal conductivity of all proposed grout samples was measured at saturation and dry conditions. The thermal conductivity of a grout comprising only PFA and cement (basic grout) was measured at dry and saturated conditions. The results indicated that thermal conductivity was equal to 0.320 and 1.081 $W/m.K$, respectively. The thermal conductivity results of the proposed grouts are shown in Table 4-3. According to these results, the tested grouts can be categorized into three main groups.

Aggregate type	Mix	Cement	PFA	Aggregate	W/C	k_{dry}	k_{sat}
		%	%	%	%	$W/m.K$	
Course sand	A1	20	20	60	0.450	0.935	2.465
	A2	20	40	40	0.450	0.859	2.180
	A3	20	60	20	0.450	0.504	1.196
Fine sand	B1	20	20	60	0.690	0.559	1.151
	B2	20	40	40	0.540	0.503	1.145
	B3	20	60	20	0.430	0.44	1.142
Medium ground glass	C1	20	20	60	0.550	0.343	0.637
	C2	20	40	40	0.480	0.450	0.733
	C3	20	60	20	0.370	0.415	0.772
Course ground glass	D1	20	20	60	0.490	0.822	1.311
	D2	20	40	40	0.540	0.763	1.322
	D3	20	60	20	0.430	0.688	1.256
Mixed ground glass	E1	20	20	60	0.390	0.619	1.241
	E2	20	40	40	0.450	0.644	1.394
	E3	20	60	20	0.720	0.354	1.215
Fluorspar	F1	20	20	60	0.500	1.577	2.875
	F2	20	30	50	0.450	1.374	2.341
	F3	20	40	40	0.450	1.032	2.219
	F4	20	50	30	0.450	0.836	1.677
Coarse ground glass + Fluorspar	G1	20	10	25+45	0.510	1.562	2.258
	G2	20	20	20+40	0.450	1.423	2.055
	G3	20	30	15+35	0.430	1.283	1.985
	G4	20	40	10+30	0.390	1.217	1.793

Table 4-3 : Dry and saturated thermal conductivity results for proposed grouts

The first group consists of the grouts that have thermal conductivity higher than 2.0 W/m.K at saturation. This was obtained in group A and F where the PFA was blended with coarse sand and fluorspar respectively. Figure 4-8 a and b show the thermal conductivity values of these groups respectively. In both groups, it can be noted that the amount of coarse sand or fluorspar required obtaining thermal conductivity higher than 2.0 W/m.K was greater than 40% by weight. In other words, the amount of the PFA was less than 40% by weight. In group A, the enhancing material was coarse sand. The high values of thermal conductivity can be attributed to the pure content of quartz that possesses high thermal conductivity. Also, the large particle size of the sand helps to raise the thermal conductivity where coarser sand is more conductive than finer. In group F, the enhancement can be attributed to presence of the iron components in fluorspar (about 65%) which have very high thermal conductivity.

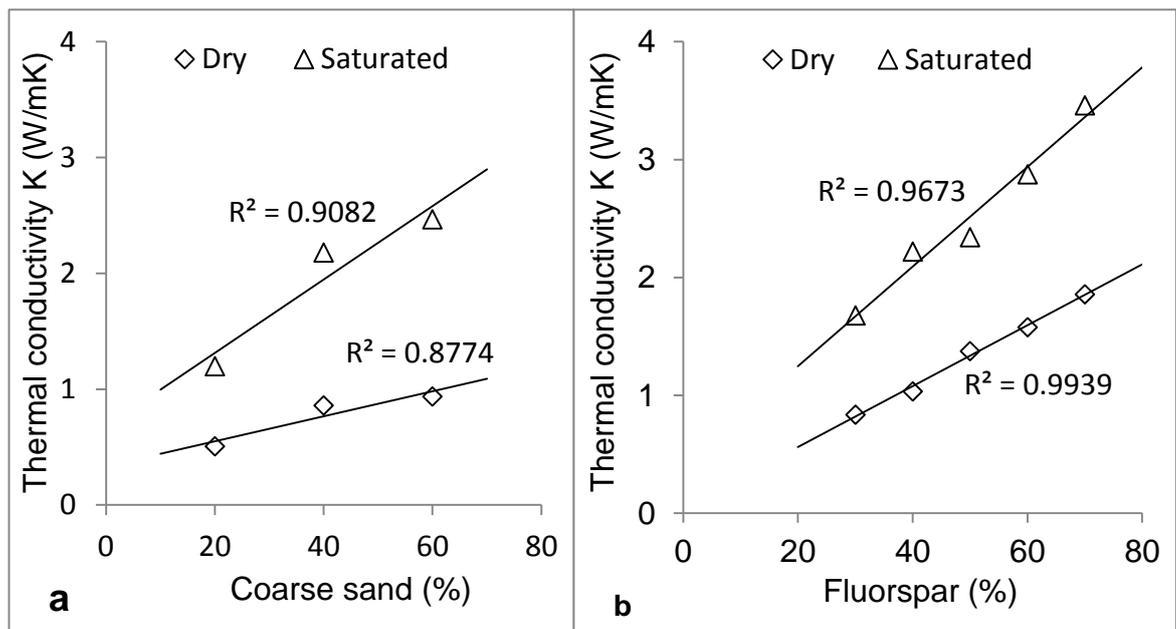


Figure 4-8 : Plot of thermal conductivity PFA- based grout versus percentage of (a) coarse sand and (b) Fluorspar.

The second group represents the grouts that have thermal conductivity ranging between 1.500 and 2.00 W/m.K at saturation. This range has been achieved in group G where the PFA was blended with fluorspar and coarse ground glass as can be seen in Figure 4-9. The results also show that the dry thermal conductivity has been significantly enhanced (from 0.32 to 1.423 W/m.K at 20% of PFA). The

ground glass relatively has low thermal conductivity compared with pure quartz sand due to low amount of quartz content (66%). Because of the large particle size of the ground glass, the fluorspar and the PFA worked as filling material providing good mix gradation, consequently voids reduced and more contact points between grout particles occurred. This explains the significant enhancement observed in the dry thermal conductivity taking into consideration the high thermal conductivity of the fluorspar.

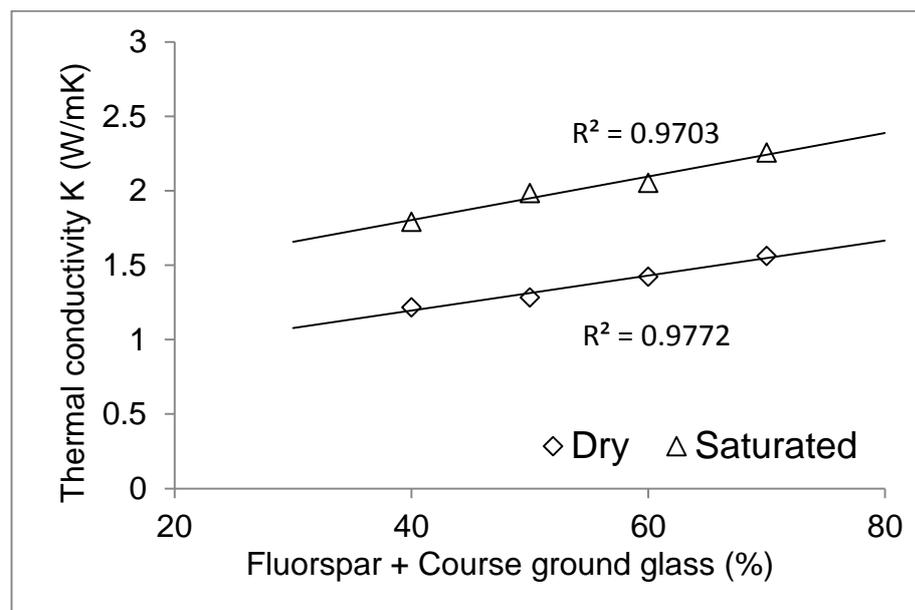


Figure 4-9 : Plot of thermal conductivity PFA- based grout versus percentage of Fluorspar + coarse ground glass

The third group represents grouts with thermal conductivity less than 1.500 $W/m.K$ at saturation. This was observed in groups B, C, D and E where the PFA was blended with fine sand, and medium, coarse and mixed ground glass, respectively (see Figure 4-10 a-d). Excluding group C, where the thermal conductivity was very low and negative enhancement has been noticed, it was remarkable that at saturation the horizontal trends indicated that no further improvement can be achieved at different mix proportions. The low enhancements of thermal conductivity that were achieved in these groups can be attributed to the low thermal conductivity of the added materials in conjunction with the poor particle size distribution of the mix.

From the above classification, it is clear that the enhancement of the thermal conductivity depends on the thermal conductivity of the added material compared

with PFA as well as the relative percentage of each component in the mix. Another important observation is that in grouts that have thermal conductivity higher than 1.50 W/m.K (groups A, F and G) the percentage of PFA higher than 40% by weight will significantly decrease the thermal conductivity. Furthermore, higher percentages of PFA needed more cement for the consistency of the grout. Also, the low density of PFA compared with other mix components should be considered in the volumetric fraction of each mix constituents. Therefore, the practical percentage of PFA can be considered between 20 to 40% by weight.

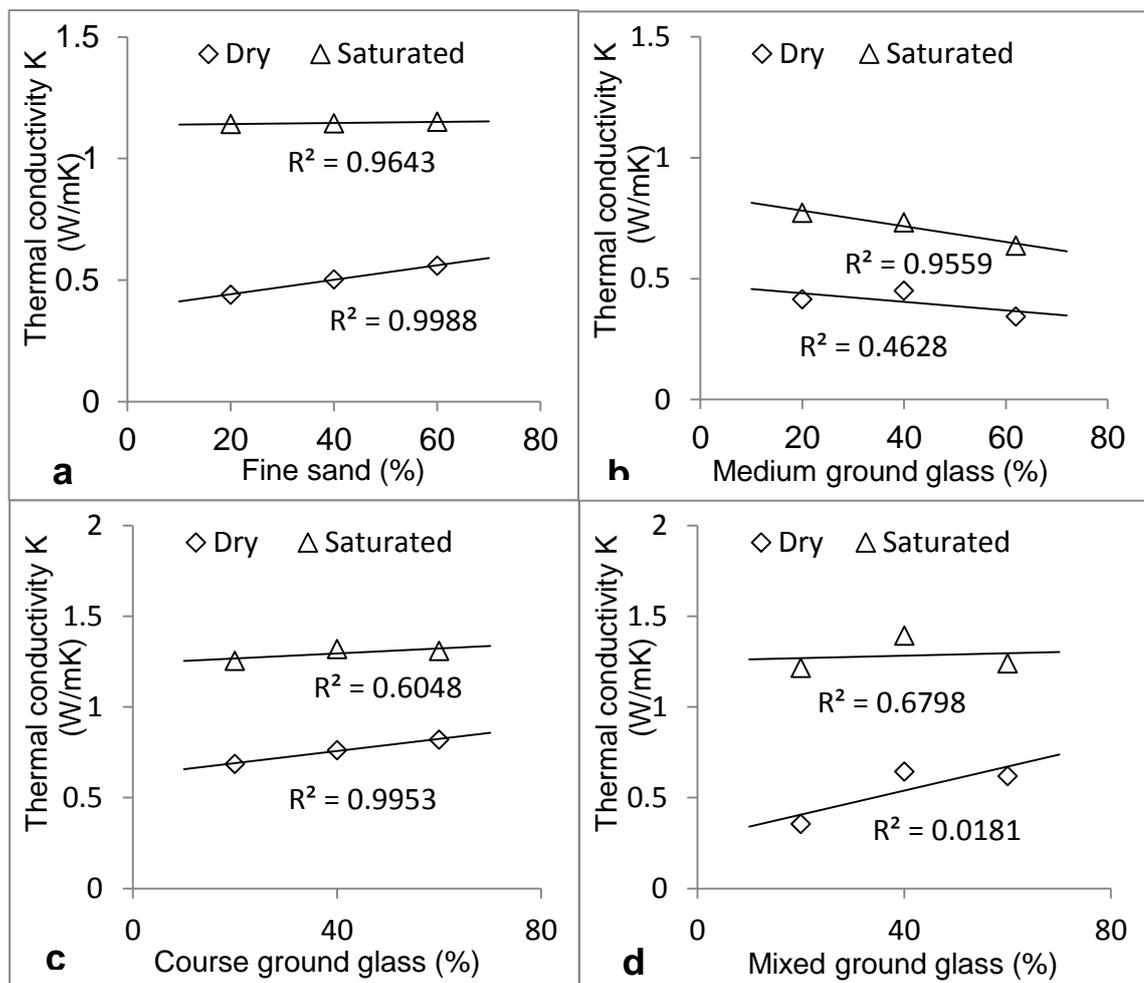


Figure 4-10 : Plot of thermal conductivity PFA- based grout versus (a) fine sand (b) medium ground glass (c) coarse ground glass (d) mixed ground glass.

The voids also can affect the thermal conductivity of the grout. This parameter is mainly linked to the water/cementitious material ratio (w/c) and the degree of compaction. Increasing water in the mix will improve its fluidity; however more voids can arise. Therefore, it is required to minimize the water/cementitious ratio in order to reduce the voids, and consequently higher thermal conductivity can

be acquired. Usually, this parameter is controlled by the workability requirements for pumpability. In the experiments presented in this work the water/cementitious material ratio ranged between 0.39 to 0.55 depending on the mix proportions and the materials used. It is also expected that the field thermal conductivity of the grout would be higher than that measured in laboratory due to the self-weight compaction of the fresh mix in the borehole.

4.6.1.1. Grout selection

The thermal conductivity of the grout should be equal to or greater than the ground formations as the efficiency of the borehole is directly linked with the thermal properties of the grout (Smith and Perry, 1999). Lee et al. (2010) proposed a thermal conductivity range of 1.7 to 2.1 $W/m.K$ for grouts combined with most existing ground types. According to Busby et al. (2009), the ground thermal conductivity in UK vary between 0.9 to 2.3 $W/m.K$. Therefore, groups A, F and G can be considered as appropriate grouts from thermal viewpoint. However, comparison between these groups considering other parameters such as permeability and the used material shows that group G, where the PFA is blended with cement, coarse grounded glass and fluorspar with dry and saturated thermal conductivity between 1.793 and 2.055 $W/m.K$ and 1.217 and 1.423 $W/m.K$ respectively, can be considered as the most appropriate group. This group has an advantage of relatively high thermal conductivity at dry condition which is a very important as the thermal conductivity can be significantly reduced by the loss of water. Delaleux et al. (2012) warned that for each 10% reduction in water content there is a reduction in thermal conductivity of the grout by 1 $W/m.K$ for their proposed grout. Also, this group comprises a reasonable amount of ground glass and has a low permeability value.

From group G, the grout G3 that consist of 20% cement, 30% PFA, 15% coarse ground glass and 35% fluorspar by weight with dry and saturated thermal conductivity of 1.283 and 1.985 $W/m.K$ respectively can be considered more practical as it comprises a considerable amount of PFA and ground glass with acceptable corresponding thermal conductivity.

4.6.1.2. Comparison with other grouts

Comparing this grout with some available grouts, the optimized grout formulation has a thermal conductivity two times, or more, higher than that of bentonite and neat cement grout. The thermal conductivity of the proposed grout was 1.985 W/m.K when tested in the laboratory after wet cured. This compares with 0.80 to 0.87 W/m.K for neat cement grout, 0.75 to 0.80 W/m.K for conventional high solids bentonite grout and 1.46 W/m.K for thermally enhanced bentonite at wet conditions. The thermal conductivity of bentonite drops to 0.40 W/m.K and that of thermally enhanced bentonite declines to 0.50 W/m.K when dried out whereas the suggested grout only drops to 1.283 W/m.K . Therefore, this grout is particularly suited to conditions where drying of the grout may occur. Allan and Philippacopoulos, 1998 designed a grout (Mix111) has thermal conductivity of 2.19 W/m.K . After field test conducted on 250 ft deep borehole, they concluded that the thermal resistance was reduced by 35% compared with high solid bentonite grout and 16% compared with thermally enhanced bentonite. Also, they stated that the first installation can be reduced at least 10% and the bore length can be reduced by 20 to 30%. The selected PFA-based grout has approximately similar thermal conductivity (1.985 W/m.K). Therefore, it is expected that using this grout with London Clay Formation optimal performance and cost savings would be achieved.

Different thermal enhancing materials are used to increase the thermal conductivity of the grouts. Some of these materials can provide superior enhancement such as compressed expanded natural graphite (Delaleux et al., 2012), graphite with silica sand (Chulho Lee et al., 2010) and silica sand (Allan and Philippacopoulos, 1998) in which the thermal conductivity can reach 5, 3, and 2.46 W/m.K respectively. However, the purpose of these grouts was to enhance the thermal conductivity without any economic considerations as the used materials can be expensive. In the PFA based grout about 60% by volume is unwanted cheap materials (PFA and ground glass).

4.6.2 Permeability

This is a very important parameter as it seals and prevents the borehole heat exchanger from being contaminated especially where ground water is expected.

The permeability of the grout is highly influenced by the texture, particle shape, gradation, and mineralogy of the materials constitute the grout. Table 4-4 shows the permeability values of the grouts in group G which has been selected as the proper grout from thermal viewpoint. It is clear that as the percentage of PFA increases the permeability decreases. This can be attributed to the size, shape and pozzolanic reaction of PFA (UKQAA, 2006).

According to Cerutti (2010) the value of the permeability of the borehole grouts should not exceed $1.0 \times 10^{-9} \text{ m/s}$. This means that the selected grout G3 provides low permeability that can fairly meets the waste containment criterion limit. Compared with another grouts such as cement silica sand grout having permeability of 10^{-9} m/s (Allan and Philippacopoulos, 1998) and cement paste backfill with value of 10^{-7} m/s (Fall et al., 2009). This grout has approximately similar permeability as cement silica sand grout although super plasticizer and bentonite have been used in the later.

Grout	W/C	Initial head	Final head	Time	Permeability
	%	(m)	(m)	(S)	m/s
G2	0.45	0.132	0.840	79200	3.31×10^{-9}
G3	0.43	0.132	0.985	84600	2.01×10^{-9}
G4	0.39	0.132	0.750	164520	1.99×10^{-9}

Table 4-4 : Permeability of the selected group (G)

4.6.3 Grout flow

Inadequate flow may lead to difficulty in pumping and could create space or holes within the confines of the borehole, and thus results in poor contact between the wall of the borehole and backfilled grout with consequent poor performance of GSHP application. For the selected grout (G3), the flow was found to be around 600 mm at water/cementitious material ratio equals to 0.43. The minimum criterion required by UKQAA 2006 is 450 mm. It should be noted that the required grout flow can vary according to the pump type.

4.6.4 Shrinkage

The shrinkage of grout is equally important like other properties of the grout as this may lead to partial contact between borehole wall and grout if it occurs. The results of the shrinkage tests indicated that no noticeable shrinkage was observed after 27 days for all types of grouts. This can be attributed to the low percentage of cement used in the grout mixes as well as to the good shrinkage properties of the PFA.

4.7 Summary

The purpose of this work was to produce a thermal grout that can be used as a backfill material in borehole heat exchangers using unwanted industrial and domestic materials (PFA and Ground glass) with relatively high thermal conductivity and economically effective. To achieve this purpose, the thermal conductivity of seven different PFA based grouts at different mix proportions have been measured at dry and saturation. The thermal conductivity was measured using a new thermal cell that utilizes the steady state technique. The thermal conductivity of PFA blended only with cement was very low. Fine sand, coarse sand, ground glass, and fluorspar have been tested as thermally enhancing materials. The results highlight the effect of mineralogy and the gradation of the mix constituents on the thermal conductivity of the grout. Low enhancement has been achieved using fine sand or ground glass. In contrast, coarse sand or fluorspar can provide higher enhancement. Also, the results show that a combination of fluorspar with coarse ground glass can provide good enhancement in both dry and saturated conditions. Moreover, the experiments showed that the percentage of PFA that can be used as a portion of thermal grout, to achieve practical thermal and rheological properties, should not exceeded 40% by weight. The grout that consist of 20 % cement, 30% PFA, 15% coarse ground glass and 35% fluorspar by weight with dry and saturated thermal conductivity of 1.283 and 1.985 $W/m.K$ respectively can be considered as the suitable grout that can be used successfully in UK. The selection was based on the thermal conductivity of the grouts compared with the thermal conductivity of the ground considering other requirements such as permeability and the use of the unwanted materials. Using this grout, the thermal resistance of the borehole is expected to be reduced by 35% compared with high solids bentonite grout and 16%

compared with thermally enhanced bentonite. Also, a reduction by 20 to 30% of borehole length accompanied with a reduction of 10% in the first cost installation are expected to be achieved. Thus it is expected that with London Clay Formation optimal performance of borehole heat exchangers and cost savings would be achieved using the selected grout.

Chapter 5 : Thermal conductivity of Tripoli Sand

5.1 Introduction

The thermal properties of soils are of importance in many thermo-active ground structures such as energy piles and borehole heat exchangers (Brandl, 2006). Determination of heat flow magnitude in these structures is highly dependent on the thermal properties of the ground.

As heat transfer in soils occurs mainly by conduction, with convection playing significant roles only in highly permeable soils such as gravel, the major thermal properties that are of interest are the thermal conductivity k and the thermal capacity c . While it is possible to determine the heat capacity per unit volume of soil with fairly good accuracy, numerous problems are encountered in the determination of thermal conductivity (Kersten, 1949; Tarnawski et al., 2000a; Nusier and Abu-Hamdeh, 2003).

Soils are either two or three phase material that consists of mineral particles, organic matter and pores which may contain water or air or both. The molecular thermal conductivity of soil solids is higher than that of water and air. The thermal characteristics of the soil component can be widely different. Thermal conductivity of soils has been found to be a function of several parameters such as: dry density, water content, mineralogy, temperature, particle size, particle shape and volumetric proportions of the soil constituents (Nusier and Abu-Hamdeh, 2003).

This chapter can be considered as a case study carried out on the measurement of thermal conductivity of a sandy soils that has not been previously thermally tested. The soil tested in this work is a sandy soil located in North Africa known as Tripoli sand. This sandy soil is found in a large area surrounding the city of Tripoli in Libya and also in many areas of the Sahara desert. The obtained results will allow for further investigations of the thermal properties of soils in a different region (North Africa). Also, the results can be considered as a data base that will

help in the design of any GSHP systems that may be established in that particular area.

The work was focusing on the effect of porosity n and degree of saturation S_r on thermal conductivity of such soils as these two parameters have a remarkable effect among all factors that can be interfering. The measurement was carried out using steady state method (the new apparatus) and transient state method (single probe method). The steady state equipment used in this experimental work has been explained in detail in chapter 3. The thermal needle probe used in this study was a commercially manufactured probe referred to as a KD2 Pro thermal properties analyser manufactured by Decagon Devices. The experimental results have been used to validate some selected empirical and semi theoretical models. Finally, an empirical equation based on the experimental results has been produced to estimate the thermal conductivity of Tripoli sand at all possible field conditions.

5.2 Experimental Methodology

5.2.1 Materials

The soil tested in this work is a sandy soil obtained from North Africa known as Tripoli sand. This sandy soil is found in a large area surrounding the city of Tripoli in Libya and also in many areas of the Sahara desert. The samples tested were extracted from a depth of one meter at a distance of 2.0 km south of the centre of Tripoli. It has a colour in between golden yellow to orange with soft texture in dry condition (Figure 5-1).



Figure 5-1 : Dry Tripoli sand sample

Sieve analysis following BS 1377, indicates that this soil can be classified as a fine sand with coefficients of uniformity and curvature of 1.83 and 0.742, respectively (Figure 5-2). Sieve analysis also revealed that 3.52% of Tripoli sand is fines. The mineralogical composition of this sample, determined by X-ray fluorescence, reveals that 93.25 % of the soil solids are silica (Silicon Dioxide) with negligible amounts of other materials (Table 5-1).

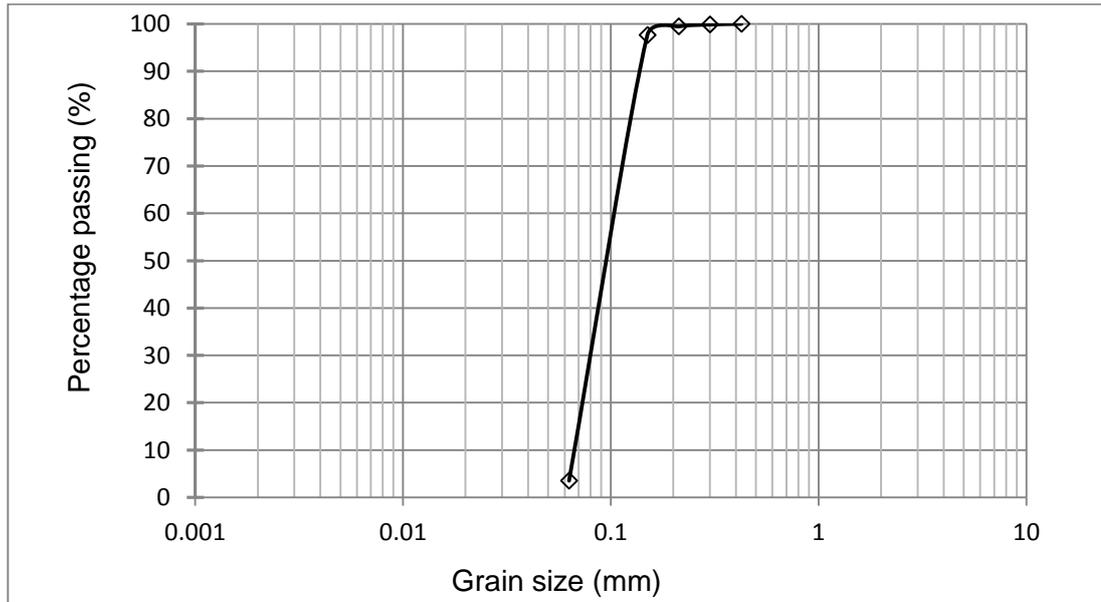


Figure 5-2 : Grain size distribution for Tripoli sand

Material	Percentage
SiO ₂	93.25
TiO ₂	0.202
Al ₂ O ₃	2.610
Fe ₂ O ₃	0.950
MnO	0.012
MgO	0.170
CaO	1.040
Na ₂ O	0.240
K ₂ O	1.040
P ₂ O ₅	0.019
SO ₃	<0.002

Table 5-1 : Compositions of Tripoli sand, determined by X-ray fluorescence (Department of Geology, University of Leicester, UK).

5.2.2 Steady state thermal conductivity measurement

The thermal conductivity of Tripoli sand has been measured at different saturation degrees and porosities. The new steady state apparatus has been used for this purpose. The design of the apparatus is based on the application of Fourier's law where a one-directional uniform heat flux is generated through two identical specimens. Using a heater disc placed between two identical specimens, a thermal gradient parallel to the axes of the specimen can be generated. In order to eliminate the radial heat losses caused by ambient temperature interference (ATI), an insulation layer surrounded by a thermal jacket was used. Full details of this apparatus have been illustrated in chapter three.

5.2.2.1 Sample preparation

The study focused on the effect of degree of saturation on the thermal conductivity at different levels of porosity of Tripoli sand soil. For interpretation of the test data, both porosity and saturation degree were artificially controlled. Four levels of porosity (dry densities) were chosen (0.400, 0.430, 0.460, and 0.490). Each level comprises five degrees of saturation (0.00, 0.10, 0.25, 0.50, and 0.60). This resulted in twenty tests being performed. Table 5-2 shows the theoretical details of the twenty different samples

The soil was firstly oven dried for 24hrs and allowed to cool in a dry place before being used. For each particular condition, the required water content, the dry density, and the wet density can be calculated using the following relations.

$$e = \frac{n}{1-n} \quad 5.1$$

$$w = \frac{e \cdot S_r}{G_s} \quad 5.2$$

$$\rho_d = \frac{G_s \cdot \rho_w}{1+e} \quad 5.3$$

$$\rho_{wet} = \rho_d(1 + w) \quad 5.4$$

where e is the void ratio, n is the porosity, w is the water content, S_r is the degree of saturation, G_s is the specific gravity of the solid particles, ρ_w is the water density, ρ_d is the dry density of the soil and ρ_{wet} bulk density of the soil.

	n	e	S_r	w	ρ_{dry}	ρ_{wet}	Volume	M_{dry}	M_{wet}
	--	--	--	--	$g.cm^{-3}$	$g.cm^{-3}$	cm^3	g	g
1	0.490	0.961	0.00	0.000	1.352	1.352	760	1027	1027
2	0.490	0.961	0.10	0.036	1.352	1.401	760	1027	1064
3	0.490	0.961	0.25	0.091	1.352	1.474	760	1027	1120
4	0.490	0.961	0.50	0.181	1.352	1.597	760	1027	1213
5	0.490	0.961	0.60	0.218	1.352	1.646	760	1027	1251
6	0.460	0.852	0.00	0.000	1.431	1.431	760	1088	1088
7	0.460	0.852	0.10	0.032	1.431	1.477	760	1088	1123
8	0.460	0.852	0.25	0.08	1.431	1.546	760	1088	1175
9	0.460	0.852	0.50	0.161	1.431	1.661	760	1088	1262
10	0.460	0.852	0.60	0.193	1.431	1.707	760	1088	1297
11	0.430	0.754	0.00	0.000	1.511	1.511	760	1148	1148
12	0.430	0.754	0.10	0.028	1.511	1.554	760	1148	1181
13	0.430	0.754	0.25	0.071	1.511	1.618	760	1148	1230
14	0.430	0.754	0.50	0.142	1.511	1.726	760	1148	1311
15	0.430	0.754	0.60	0.171	1.511	1.769	761	1149	1346
16	0.400	0.667	0.00	0.000	1.590	1.590	760	1208	1208
17	0.400	0.667	0.10	0.025	1.590	1.630	760	1208	1239
18	0.400	0.667	0.25	0.063	1.590	1.690	760	1208	1284
19	0.400	0.667	0.50	0.126	1.590	1.790	760	1208	1360
20	0.400	0.667	0.60	0.151	1.590	1.830	760	1210	1393

Table 5-2 : Theoretical design of Tripoli sand specimens

According to the presumed saturation degree and porosity, a soil sample with certain moisture content was prepared. The moisture content of the sample was measured by the drying method, ensuring accurate moisture content. By knowing the volume of the specimen the required wet mass to obtain the predefined dry density can be calculated.

The positions of the sink discs in the two specimen cylinders were adjusted to maintain the desired volume. Then the prepared two wet masses were compacted in the two specimen cylinders to the required dry density using conventional compaction procedures (Figure 3-5). Upon completion, the samples were weighed to check the accuracy of the dry density, if the dry density was far from the required, the preparation was repeated.

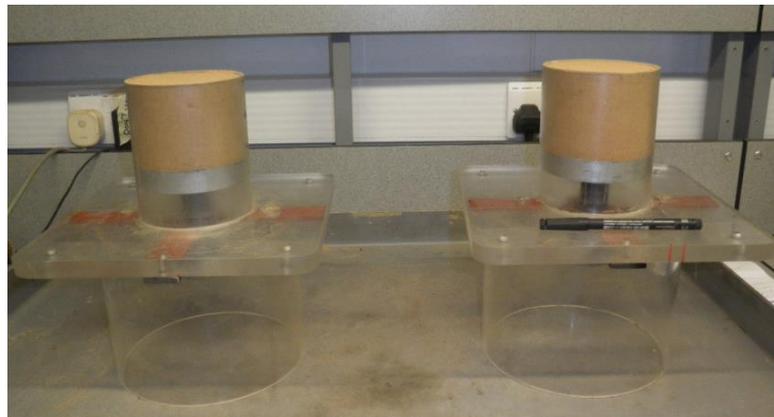


Figure 5-3 : Two specimen cylinders with soil samples

5.2.2.2 Test procedure

After the preparation of the specimens was completed, the two specimen cylinders containing the soil samples were then slotted and fixed into the insulating cylinder. This can be done by means of short studs used to fasten the two acrylic cover plates from each side. The length of the specimen's cylinders was designed to insure complete contact between the heater disc and the two specimens when they reach the final position inside the insulating cylinder.

To monitor the temperature gradient along each specimen length, four thermocouples were laterally pushed to the desired positions at intervals of 00, 30, 60, and 80 mm from the heater. Another two thermocouples were used to monitor the temperature of thermal jacket and room temperature. The room

temperature was adjusted to the desired level. The apparatus then left for some time to allow soil specimens and the thermal cell reaching thermal equilibrium. This was checked from the continuous readings of thermocouples temperature on the Pico-logger software. After equilibrium was reached, the DC power supply and the thermal jacket were switched on, and the test was allowed to reach the steady state. This was achieved when the reading of the thermocouples were constant for at least one hour. The output temperature of each thermocouple can be plotted or tabulated versus time. Figure 5-4 is an example of temperature versus time curve. The obtained data was then transferred to spread sheet for calculation and analysis.

Using the equation developed by Fourier for heat conduction with one dimensional heat flow at steady-state condition, the effective thermal conductivity k can be determined as follows:

$$k = \frac{1}{2} \frac{q}{A} \frac{L}{\Delta T} \quad W/m.K \quad 5.5$$

where: q is the rate of heat transfer, ΔT is the temperature drop across the specimen, L is the specimen length and A is the cross sectional area.

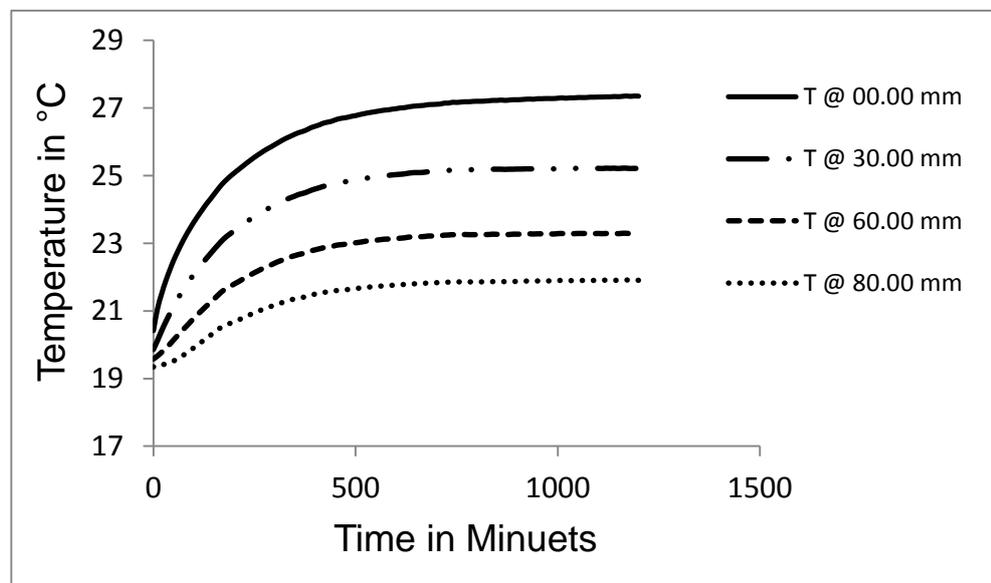


Figure 5-4 : Typical temperature versus time curve

At least two thermal conductivity values were calculated using two different specimen lengths with their corresponding temperatures. The correction step that

explained in section 3.3.3. 5 was then applied to obtain the final thermal conductivity value of the tested soil specimen.

5.2.3 Transient probe method (KD2)

The transient apparatus used to measure the thermal conductivity of the same sandy sample is a commercial thermal properties analyser, KD2 (Decagon Devices Inc) section 3.4.7 showed the details of the KD2 instrument. Similar steps to the steady state case were followed for sample preparation however the specimen cylinder has different size (120 mm length and 80 mm in diameter). The test procedure was done in accordance with ASTM D 5334, 2008 and the manual of the KD2 instrument. After inserting the probe into the soil sample, a known current and voltage are applied to the probe and the temperature rise with time is recorded over a period of time. Figure 5-5 presents the set-up of the thermal conductivity measurement using KD2 instrument. The probe was calibrated prior to testing using standard material which was provided by the manufacturer.

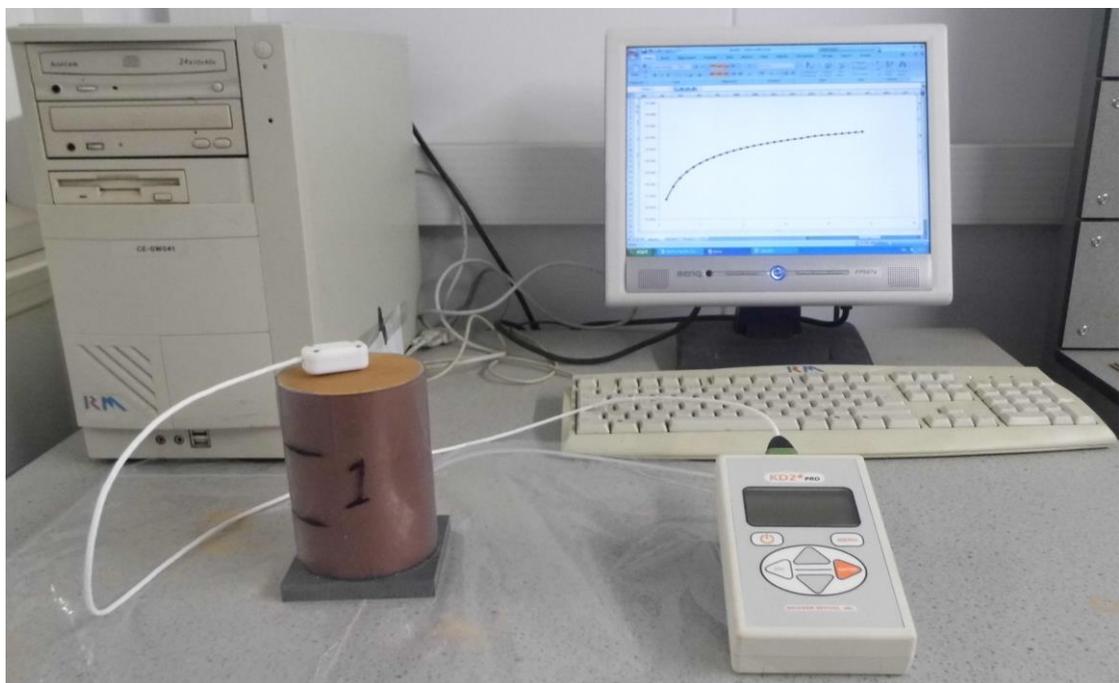


Figure 5-5 : Thermal conductivity measurement using KD2 instrument

5.3 Experimental results

The actual physical properties of twenty Tripoli sand specimens with different porosities and saturation degrees and the thermal conductivities measured using the two methods are presented in Table 5-3. From these results, several relations between physical properties and thermal conductivity of Tripoli sand can be observed and assessed. However, some others such as mineralogical composition and grain size cannot be evaluated as they were same in all tests.

	M_{wet}	w	ρ_{dry}	e	n	S_r	k (W/m.K)	
	gm	%	$g.cm^{-3}$	--	--	--	Steady	Transient
1	1027	00.55	1.344	0.972	0.493	0.015	0.348	0.180
2	1069	03.83	1.353	0.959	0.490	0.106	1.596	1.141
3	1129	09.13	1.350	0.963	0.491	0.251	1.830	1.437
4	1246	18.10	1.343	0.974	0.493	0.493	2.052	1.829
5	1260	21.00	1.315	1.015	0.504	0.548	2.151	1.918
Average			1.340	0.978	0.494			
6	1088	00.44	1.425	0.859	0.462	0.014	0.352	0.194
7	1126	03.46	1.430	0.853	0.460	0.108	1.701	1.361
8	1180	07.67	1.434	0.849	0.459	0.240	1.941	1.689
9	1287	15.84	1.425	0.859	0.462	0.488	2.135	2.132
10	1325	19.03	1.412	0.877	0.467	0.575	2.283	2.226
Average			1.425	0.859	0.462			
11	1148	00.48	1.503	0.763	0.433	0.017	0.454	0.215
12	1189	02.92	1.519	0.745	0.427	0.104	1.669	1.383
13	1235	06.92	1.513	0.752	0.429	0.244	2.060	1.960
14	1325	13.80	1.503	0.763	0.433	0.479	2.216	2.213
15	1351	16.63	1.482	0.788	0.441	0.559	2.352	2.339
Average			1.504	0.762	0.432			
16	1208	00.60	1.580	0.677	0.404	0.023	0.584	0.238
17	1231	02.52	1.579	0.678	0.404	0.098	1.679	1.606
18	1290	06.41	1.589	0.668	0.401	0.254	2.153	2.034
19	1370	12.48	1.578	0.680	0.405	0.487	2.325	2.321
20	1389	15.08	1.552	0.707	0.414	0.565	2.475	2.469
Average			1.575	0.682	0.406			

Table 5-3 : Results of effective thermal conductivity for Tripoli sand specimens

5.4 Prediction methods

A range of equations exist in the literature for the prediction of the thermal conductivity of sandy soils. Most of these equations were developed from empirical curve-fits to datasets. Therefore, they are likely to fit the data for which they were derived very well. Selected models were applied to predict the thermal conductivity of Tripoli sand specimens at different degrees of saturation and porosities. The obtained results were then validated against the results obtained from experimental tests that have been carried out in this work. In all calculations, the values of thermal conductivity of the soil particles, water and air were 7.69, 0.60 and 0.026 $W/m.K$ respectively.

5.4.1 De Vries equation (1963)

De Vries (1963) proposed a method that uses the weighted average of thermal conductivity value of each soil constituent. This method is based on Maxwell's equation for the electrical conductivity of a mixture of uniform spheres dispersed randomly in a continuous fluid (Farouki, 1986). For unsaturated soils, solid particles and air are considered to be two components immersed in the continuous water medium. The derivation of the De Vries's equation is based on the assumption of no contact between the soil's solid particles, and the values of the shape factor (g) assume that the solid particles have ellipsoidal shapes. The thermal conductivity according to De Vries is expressed as:

$$k = \frac{x_w k_w + F_a x_a k_a + F_s x_s k_s}{x_w + F_a x_a + F_s x_s} \quad 5.6$$

where $x_w = \frac{V_w}{V}$, $x_a = \frac{V_a}{V}$, $x_s = \frac{V_s}{V}$

F_s and F_a are the weighting factor depending on the shape and orientation of soil particles and air-pores respectively and equal to:

$$F_s = \frac{1}{3} \left\{ \frac{2}{1 + \left(\frac{k_s}{k_w} - 1\right) 0.125} + \frac{1}{1 + \left(\frac{k_s}{k_w} - 1\right) 0.75} \right\} \quad 5.7$$

$$F_a = \frac{1}{3} \left\{ \frac{2}{1 + \left(\frac{k_a}{k_w} - 1\right) g_a} + \frac{1}{1 + \left(\frac{k_a}{k_w} - 1\right) g_c} \right\} \quad 5.8$$

where g_a and g_c are called shape factors and expressed as:

$$g_a = 0.333 - \frac{x_a}{n} (0.333 - 0.035) \quad \text{For } 0.09 \leq x_w \leq n \quad 5.9$$

$$g_a = 0.013 + 0.944x_w \quad \text{For } 0 \leq x_w \leq 0.09 \quad 5.10$$

$$g_c = 1 - 2g_a \quad 5.11$$

Another assumption assumed by De Vries is that the thermal conductivity of air varies linearly with x_w :

$$k_a = 0.0615 + 1.9x_w \quad 5.12$$

The calculations of the thermal conductivity using De Vries procedure along with the corresponding the steady state and transient state experimental results are shown in figure 5.6.

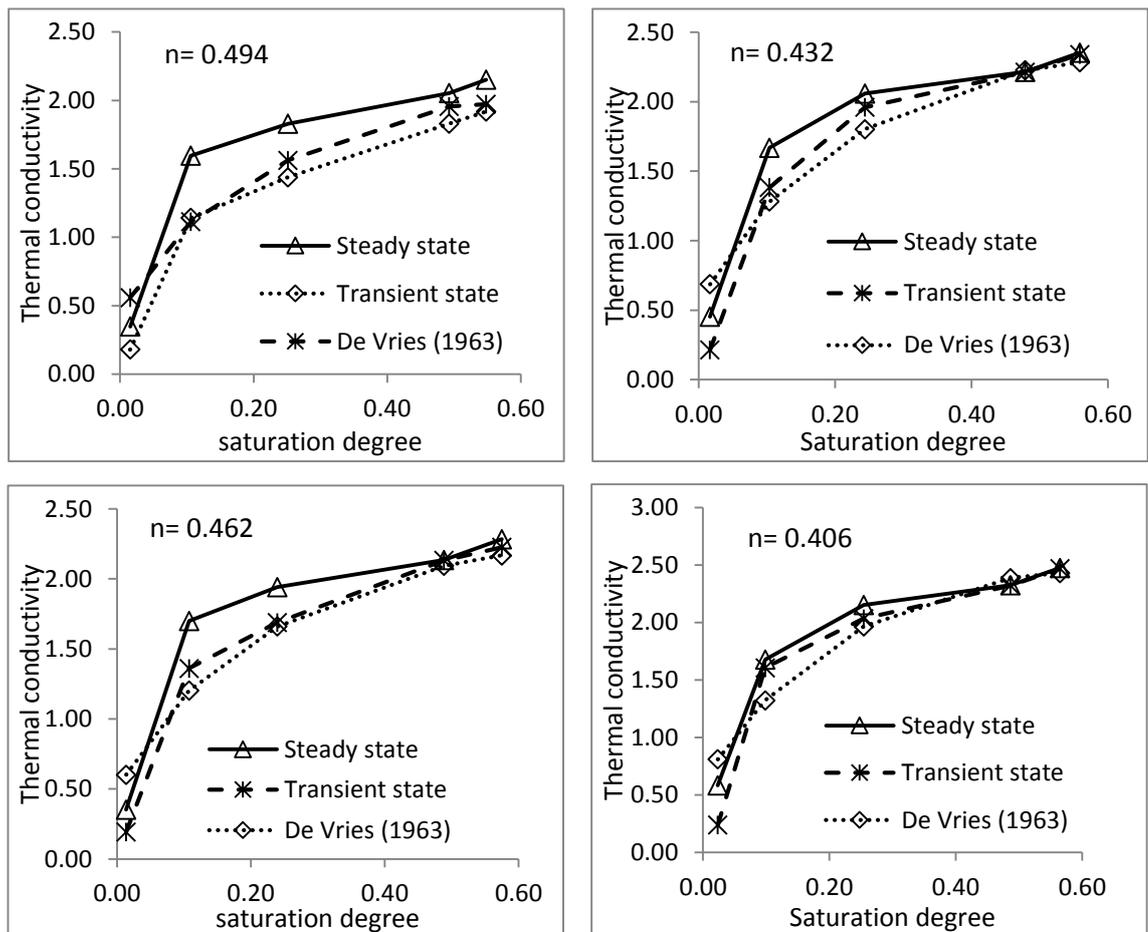


Figure 5-6 : Plots of thermal conductivity versus degree of saturation using De vries (1963) model along with experimental results for Tripoli sand

5.4.2 Johansen method (1975)

Johansen (1975) developed a method for determining the thermal conductivity of unsaturated soils based on the dry and saturated thermal conductivities when evaluated at same dry density. For natural dry soils, Johansen has proposed the following empirical equation:

$$k_{dry} = \frac{0.135\rho_{dry}+64.7}{2700-0.94\rho_{dry}} \pm 20 \quad 5.13$$

Where ρ_{dry} is the dry density in kg/m^3 , and the solid density is taken as 2700 kg/m^3 .

For saturated soils, he proposed the geometric mean equation based on the relative fraction of the soil components and their thermal conductivities.

$$k_{sat} = k_s^{1-n} k_w^n \quad 5.14$$

where n is the porosity, k_s is the solid thermal conductivity, and k_w is the water thermal conductivity.

In order to evaluate the unsaturated thermal conductivity in terms of k_{dry} , k_{sat} and degree of saturation S_r , Johansen proposed the following correlation:

$$k = (k_{sat} - k_{dry})K_e + k_{dry} \quad 5.15$$

where K_e is a function representing the influence of S_r on the thermal conductivity and expressed as:

For coarse unfrozen soils:

$$K_e = 0.7 \log S_r + 1 \quad S_r > 0.05 \quad 5.16$$

For fine unfrozen soil:

$$K_e = \log S_r + 1 \quad S_r > 0.1 \quad 5.17$$

The thermal conductivity values obtained from the application of this method on the Tripoli sand are showed in figure 5-7. It should be mentioned that the solid density used in this calculations was experimentally measured and found to be 2650 Kg. m^{-3} rather than 2700 Kg. m^{-3} as used by Johansen.

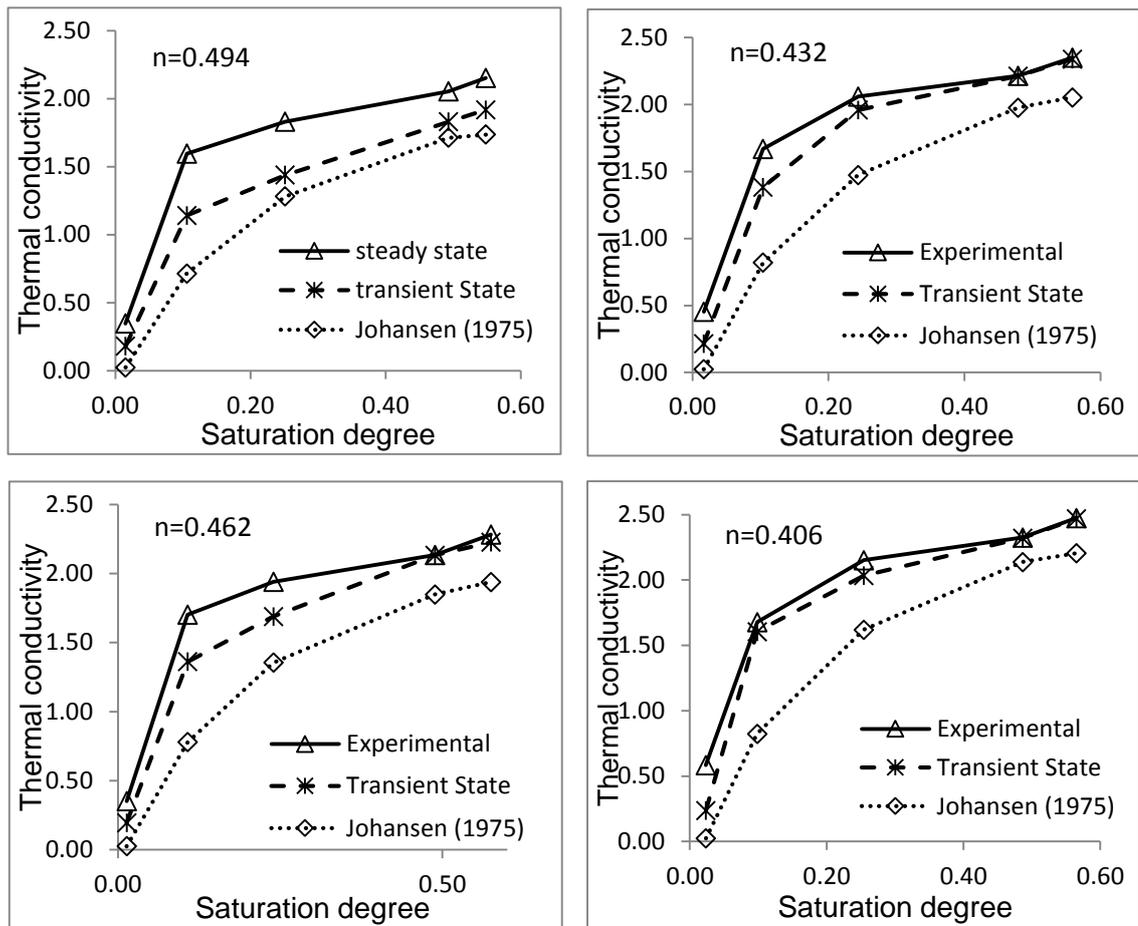


Figure 5-7 : Plots of thermal conductivity versus degree of saturation using Johansen (1975) model along with experimental results for Tripoli sand

5.4.3 Donazzi et al. model (1979)

Donazzi et al. (1979) proposed an empirically derived exponential relationship which describes the effect of the saturation degree and the porosity on the thermal conductivity. It should be noted that Donazzi et al. consider the thermal conductivity of soil grains of 4 W/m.K . They proposed the following equation:

$$k = k_w^n k_s^{1-n} \exp[-3.08n(1 - S_r)^2] \quad 5.18$$

where, n and S_r are the porosity and the saturation degree respectively.

Figure 5-8 shows the results obtained when applying the proposed empirical equation on the Tripoli sand. It should be noted that the thermal conductivity of the soil grains used in this calculation equals to 7.7 W/m.K rather than the value of 4 W/m.K used by Donazzi et al (1979).

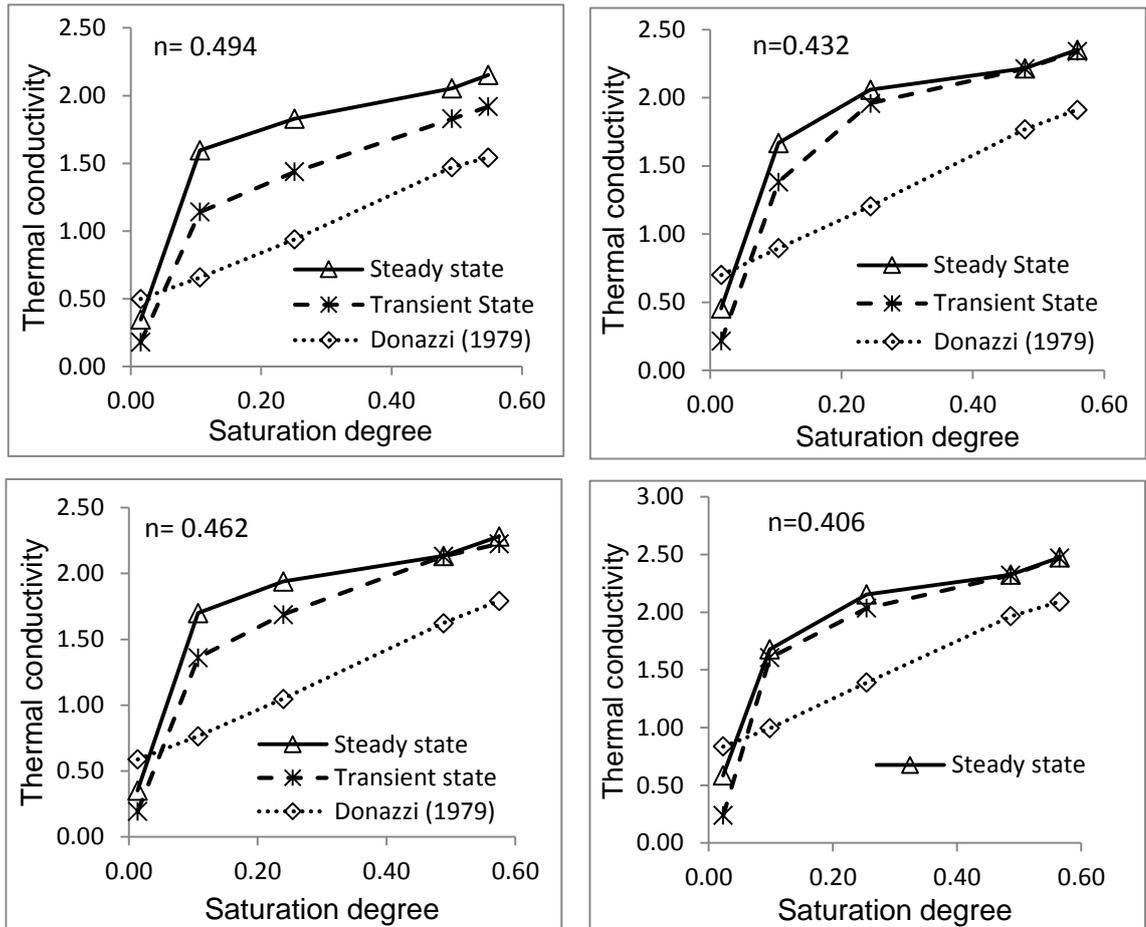


Figure 5-8 : Plots of thermal conductivity versus degree of saturation using Donazzi (1979) model along with experimental results for Tripoli sand

5.4.4 Gangadhara Rao and Singh (1999)

Gangadhara Rao and Singh (1999) suggested an empirical equation for thermal conductivity of soils based on experimental tests of four types of soil using thermal needle probe technique. They proposed a relationship that estimates thermal conductivity of soils depending upon the moisture content and density of the soils.

$$k = 10^{0.01\gamma-1}(1.07\log w + 0.715) \quad 5.19$$

where, γ is the unit weight of soil in Lb/ft^3 and w is the moisture content in percent.

The values obtained from the suggested empirical equation with corresponding to their experimental results are shown in figure 5-9.

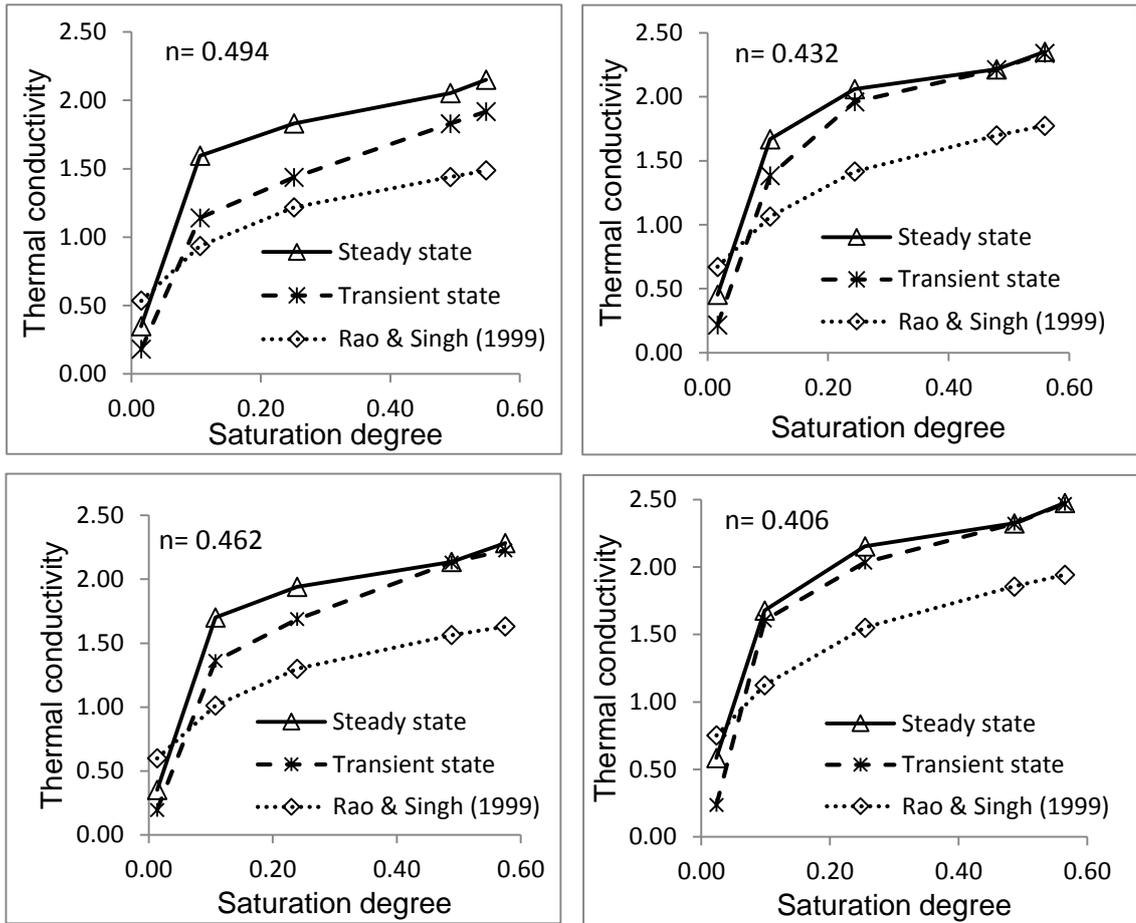


Figure 5-9 : Plots of thermal conductivity versus degree of saturation using Rao & Singh (1999) model along with experimental results for Tripoli sand

5.4.5 Côté and Konrad (2005)

Côté and Konrad (2005) modified the Johansen model to eliminate the logarithmic reliance on the saturation degree that distorted predictions of the thermal conductivity at dry condition and low degrees of saturations. The developed thermal conductivity model is based on the concept of normalized thermal conductivity with respect to dry and saturation states. They offered a modified relationship of the form:

$$k = (k_w^n k_s^{1-n} - x10^{-\eta n}) \left[\frac{aS_r}{1+(a-1)S_r} \right] + x10^{-\eta n} \quad 5.20$$

where x and η account for particle shape effect, and a accounts for soil texture effect. For fine sand, they suggested 3.55 for a , 1.7 $W/m.K$ for x and 1.8 for η .

The prediction of the thermal conductivities of Tripoli sand specimens using the Côté and Konrad equation with the corresponding experimental results are presented in figure 5-10.

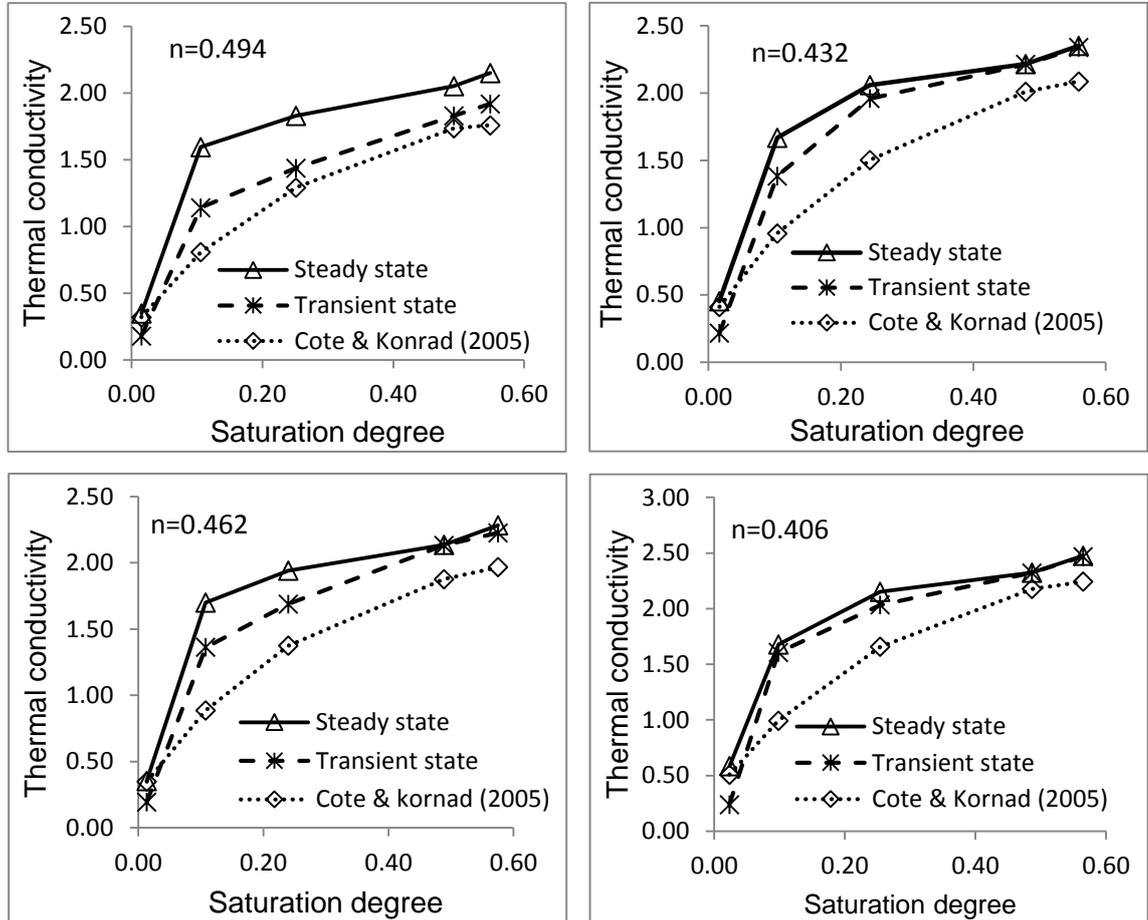


Figure 5-10 : Plots of thermal conductivity versus degree of saturation using Cote & Konrad (2005) model along with experimental results for Tripoli sand

5.4.6 Lu et al. model (2007)

Lu et al. (2007) also proposed a modification of Johansen's model. They proposed the following equation for the estimation of the thermal conductivity of sandy soils:

$$k = [k_w^n k_s^{1-n} - (b - an)] \exp[c(1 - S_r^{c-1.33})] + (b - an) \quad 5.21$$

where a , b and c are empirical parameters. The values suggested for sandy soils are 0.56, 0.51 and 0.96 respectively. Figure 5-11 shows the results of the model when compared with experimental results of Tripoli sand.

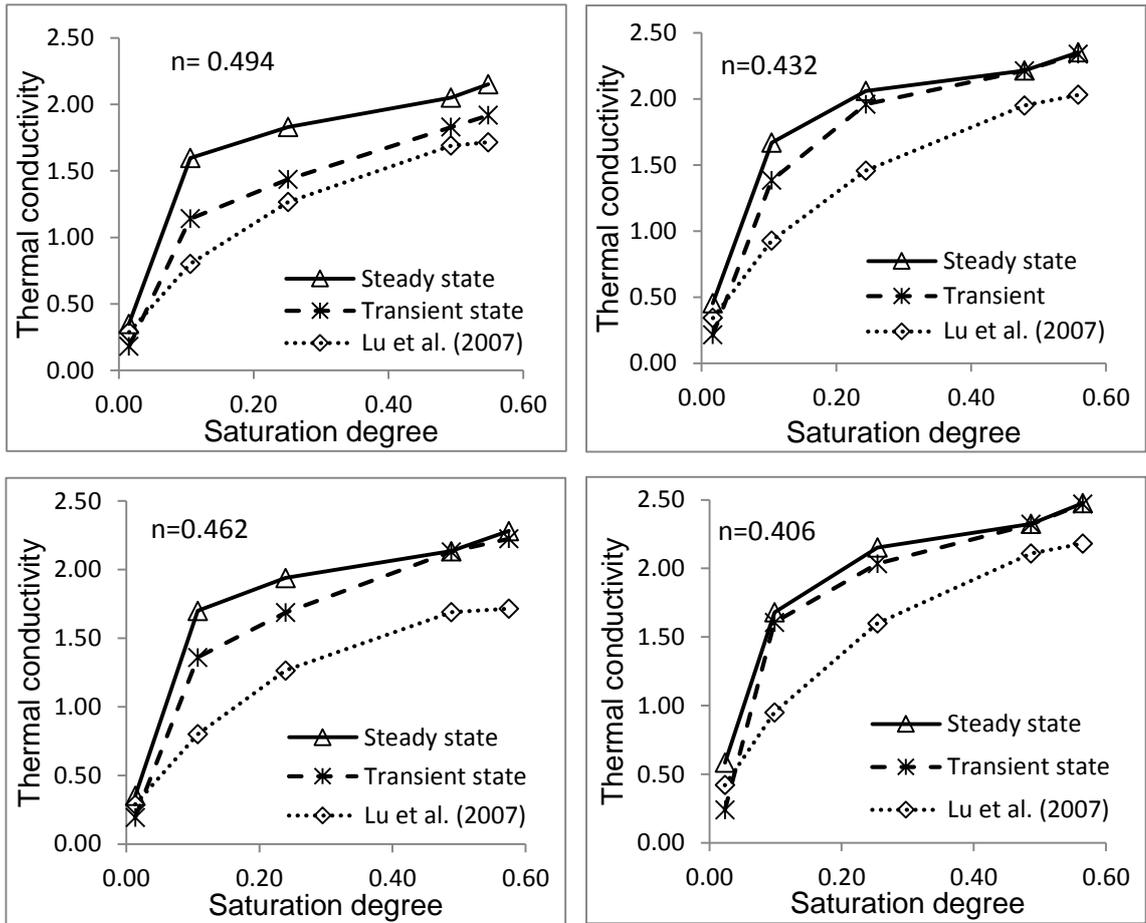


Figure 5-11 : Plots of thermal conductivity versus degree of saturation using Lu et al. (2007) model along with experimental results for Tripoli sand

5.4.7 Chen (2008)

Based on laboratory investigation of sandy soils, Chen (2008) proposed an empirical equation of thermal conductivity expressed as the function of porosity and degree of saturation. The equation is based on 80 needle-probe experimental tests on four types of sandy soils with different saturation degrees at different porosities. He proposed the following equation:

$$k = k_w^n k_s^{1-n} [(1 - b)S_r + b]^{cn} \quad 5.22$$

where b and c are empirical parameters obtained from the fitting of the measured data and equal to 0.0022 and 0.78 respectively. The comparison between the experimental results and the results obtained from Chen model is presented in figure 5-12.

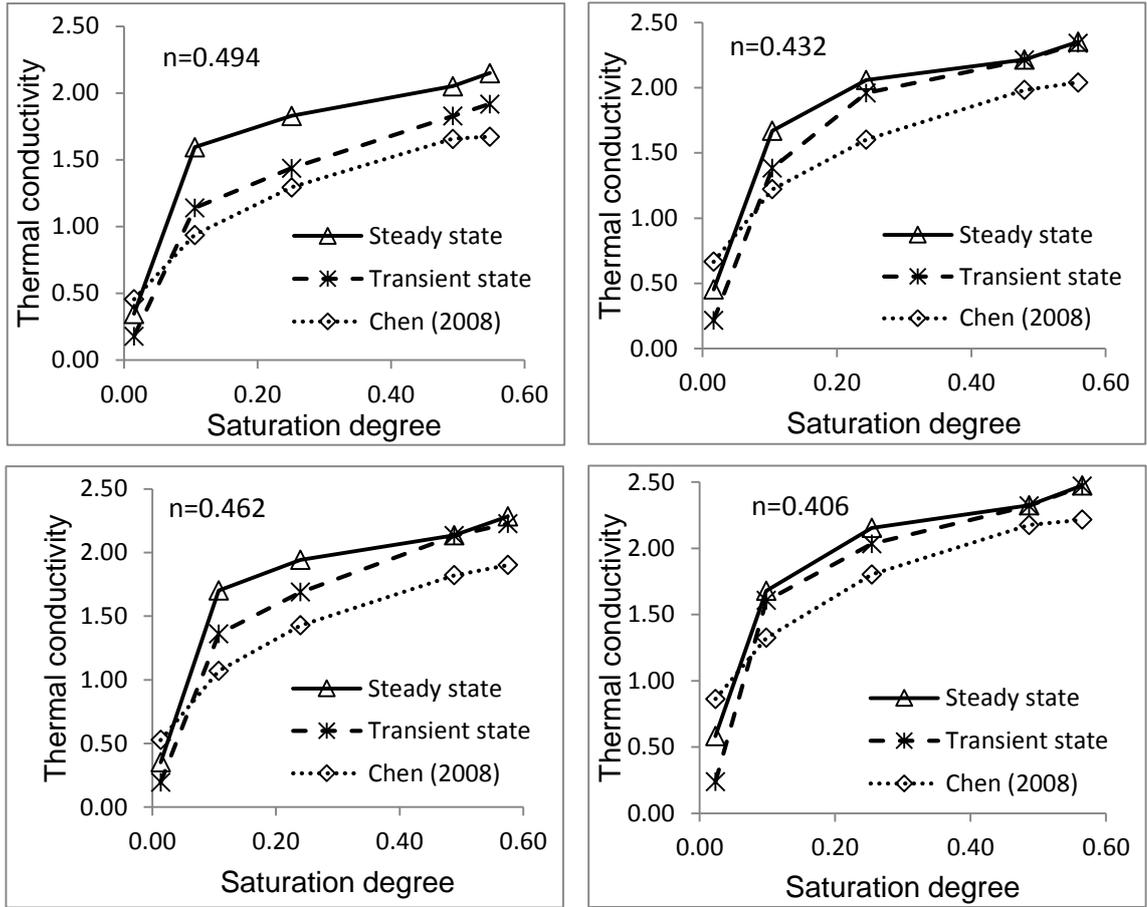


Figure 5-12 : Plots of thermal conductivity versus degree of saturation using Chen (2008) model along with experimental results for Tripoli sand

5.4.8 Haigh (2012)

Haigh (2012) proposed an analytical model based on unidirectional heat flow through a three-phase soil element. The model analyses the one-dimensional heat flow between two equally sized spherical soil particles of radius R . Two geometric parameters β and ξ are introduced to express the saturation degree and the void ratio respectively. The overall thermal conductivity can be expressed as the following:

$$\frac{k}{k_s} = 2(1 + \xi)^2 \left\{ \frac{\alpha_w}{(1-\alpha_w)^2} \ln \left[\frac{(1+\xi)+(\alpha_w-1)}{\xi+\alpha_w} \right] + \frac{\alpha_a}{(1-\alpha_a)} \ln \left[\frac{(1+\xi)}{(1+\xi)+(\alpha_a-1)x} \right] \right\} + \frac{2(1+\xi)}{(1-\alpha_w)(1-\alpha_a)} [(\alpha_w - \alpha_a)x - (1 - \alpha_a)\alpha_w] \quad 5.23$$

where,

$$\xi = \frac{2e-1}{3} \quad 5.24$$

$$\alpha = \frac{k_f}{k_s} \tag{5.25}$$

$$x = \left(\frac{1+\xi}{2}\right) (1 + \cos\theta - \sqrt{3}\sin\theta) \tag{5.26}$$

where,

$$\cos 3\theta = \frac{2(1+3\xi)(1-S_r)-(1+\xi)^3}{(1+\xi)^3} \tag{5.27}$$

Where α_w and α_a are the thermal conductivities, normalised by that of the soil solids, of water and air respectively, as found in equation (5.25).

The validation of this model against the experimental results is shown in figure 5-13.

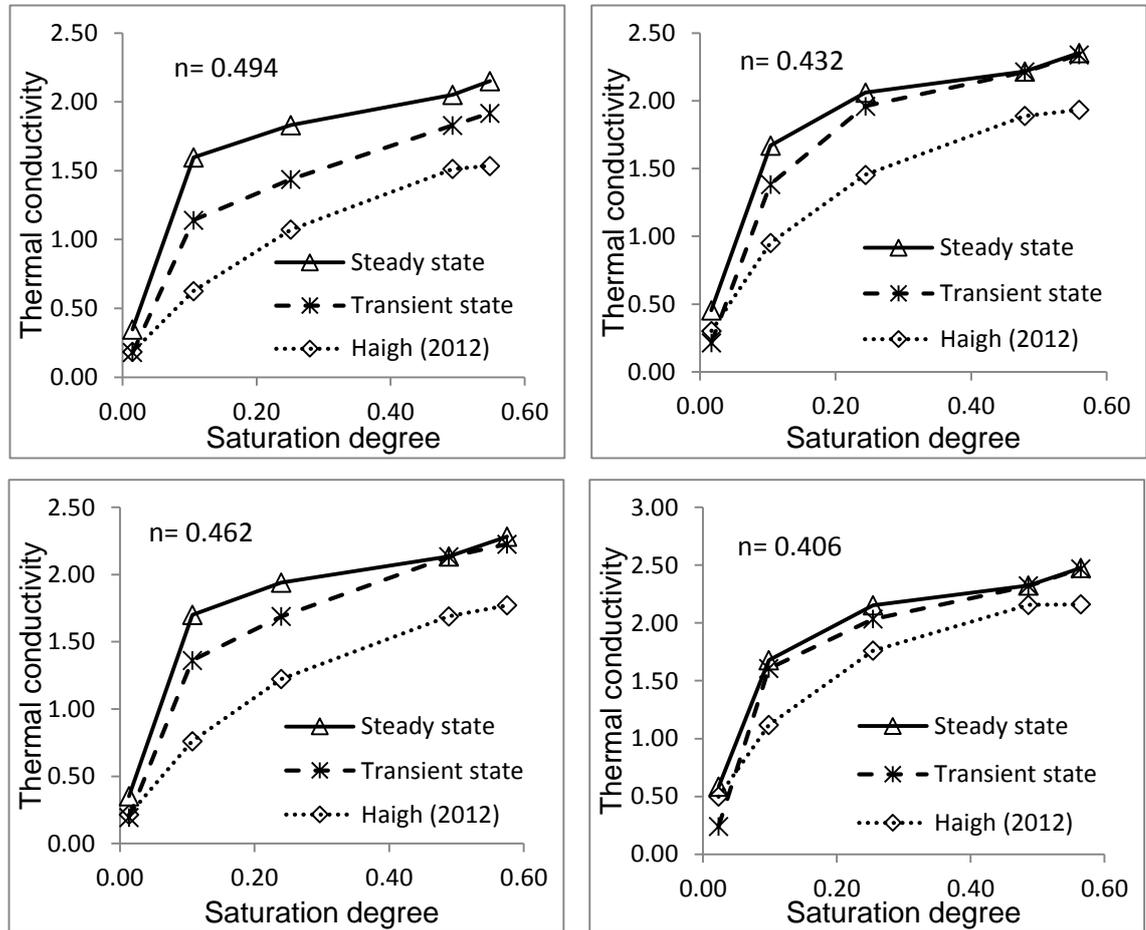


Figure 5-13 : Plots of thermal conductivity versus degree of saturation using Haigh (2012) model along with experimental results for Tripoli sand

5.5 Results discussion

The purpose of this work was to measure the thermal conductivity of Tripoli sand at different conditions experimentally. These conditions are supposed to cover most of the field conditions that may exist naturally. The obtained results were used to evaluate the effect of varying some physical properties on the thermal conductivity of such soil. Also, selected prediction models were tested to establish the validity of using such models in the calculation of thermal conductivity of this particular type of soil.

5.5.1 Steady state results versus transient state results

The thermal conductivity of Tripoli sand specimens have been measured using the new steady state apparatus and KD2 probe at four different dry densities (porosity). At each dry density, the thermal conductivity is measured at five different degrees of saturation (water content). Figure 5-14 presents the results obtained from these tests.

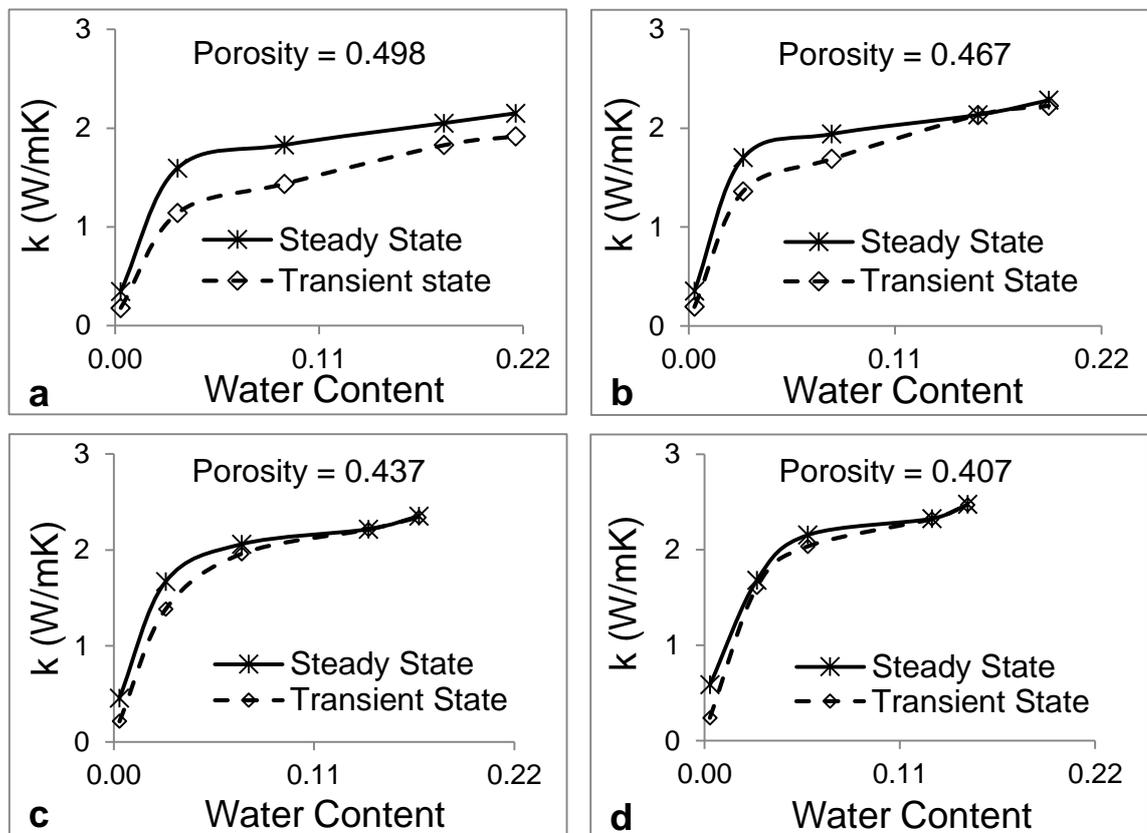


Figure 5-14 : Thermal conductivity results of Tripoli sand using steady state and transient state methods

The thermal conductivity results of Tripoli sand obtained using the KD2 instrument (transient method) against the obtained results using divide bar method (steady state method) are presented in figure 5-15.

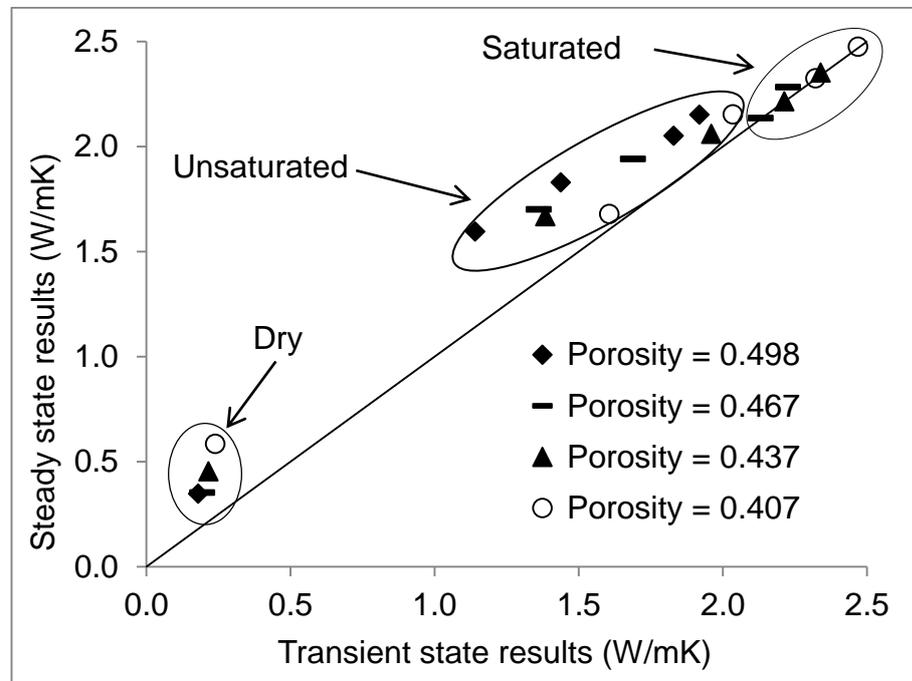


Figure 5-15 : Comparison of steady state on transient state thermal conductivity results of Tripoli sand

From these figures, it is clear that the obtained thermal conductivity results using the two methods become closer as the porosity decreases. It is also noticed that at dry conditions the discrepancy between the two methods is significant however at saturation both methods gave approximately identical values. The reasons of this discrepancy have been explained in section 3.5.7.

From these observations, it can be concluded that the results obtained by the steady state divided bar method at dry conditions can be considered more accurate than that obtained by probe method. This is because at dry condition there is no concern of moisture migration while the contact resistance in the probe methods can mislead the results significantly. At partially saturated condition both methods have a concern of the moisture migration however contact resistant in probe methods still can be a point of concern. At saturated conditions, there is no concern of the contact resistance using the probe method however similar results are obtained using the new steady state apparatus. This indicates that the factors

influencing the thermal conductivity measurement are well controlled using the new apparatus. Thus the steady state results are adopted as the thermal conductivity values of Tripoli sand.

5.5.2 Experimental results versus prediction method results

The experimental results of the thermal conductivity of Tripoli sand obtained using both the steady state thermal cell apparatus and the KD2 single probe along with the corresponding calculated values based on selected prediction methods are graphically presented in figures 16-19. The parameters used in the calculations methods are actual parameters that express the condition of tested specimens.

It can be seen that the De Vries (1963) model can be used to satisfactorily predict the thermal conductivity at high degrees of saturation. However, at low saturation levels, the model predicted higher values than were observed. This may be attributed to the assumption that the soil particles and air are considered to be immersed in a continuous water phase. This assumption is only valid at high water content. The Johansen (1975) model is not able to predict the thermal conductivity of Tripoli sand at dry condition. The main reason of that is the logarithmic dependence on the saturation ratio which leads to erroneous results at low degrees of saturation. However, at high saturations (above 50%) the model values are in good agreement with the experimental results with a deviation ranging between 8 and 19% from experimental results depending on the porosity level. The Côté and Konrad (2005) model correctly predicted the thermal conductivity of Tripoli sand at dry condition for all levels of porosity with an average deviation less than 8%. This was also observed at high saturations with average deviation around 13%. It can also be observed from figure 5-11, that the same result is captured by Lu et al. (2007). This is due to the fact that both models can be seen as a logical extension of Johansen model. It should be noted for the Lu et al. (2007) model, that the optimum fit to all test results is obtained with values $a = 2.71$ and $b = 1.65$ for the relationship between dry thermal conductivity and porosity. The graphs show that the Chen (2008) model overestimated the result of thermal conductivity at dry and low degrees of saturation of Tripoli sand with a deviation ranging from 30 to 50%. However, at high saturations the results became more consistent, especially at low porosities, and the deviation ranged between 6 to 22%. The equations derived by Haigh (2012) are relatively

complicated when compared with existing empirical models. The results obtained from the application of this theoretical model for Tripoli sand shows that this model can only provide reasonable results at nearly dry conditions. Although, these results were not consistent with the experimental results, this model can be considered as one of the important models for predicting thermal conductivity of soils as it simplifies the fluid behaviour at particle contacts at various void ratios and soil saturations.

It is also noticed that the thermal conductivity values obtained using transient method are more consistent with the predicted values especially at high porosity conditions. This is because most of prediction models were calibrated using experimental results obtained by transient methods.

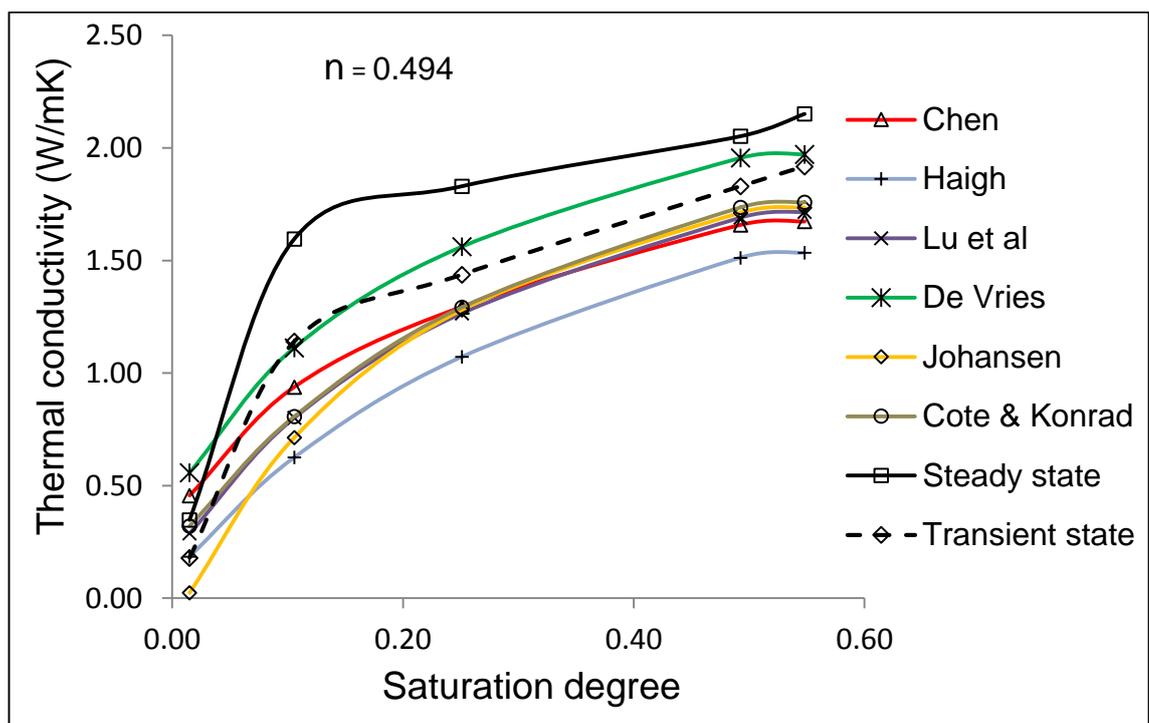


Figure 5-16 : Plot of thermal conductivity versus degree of saturation using different prediction models along with experimental results for Tripoli sand at porosity of 0.494

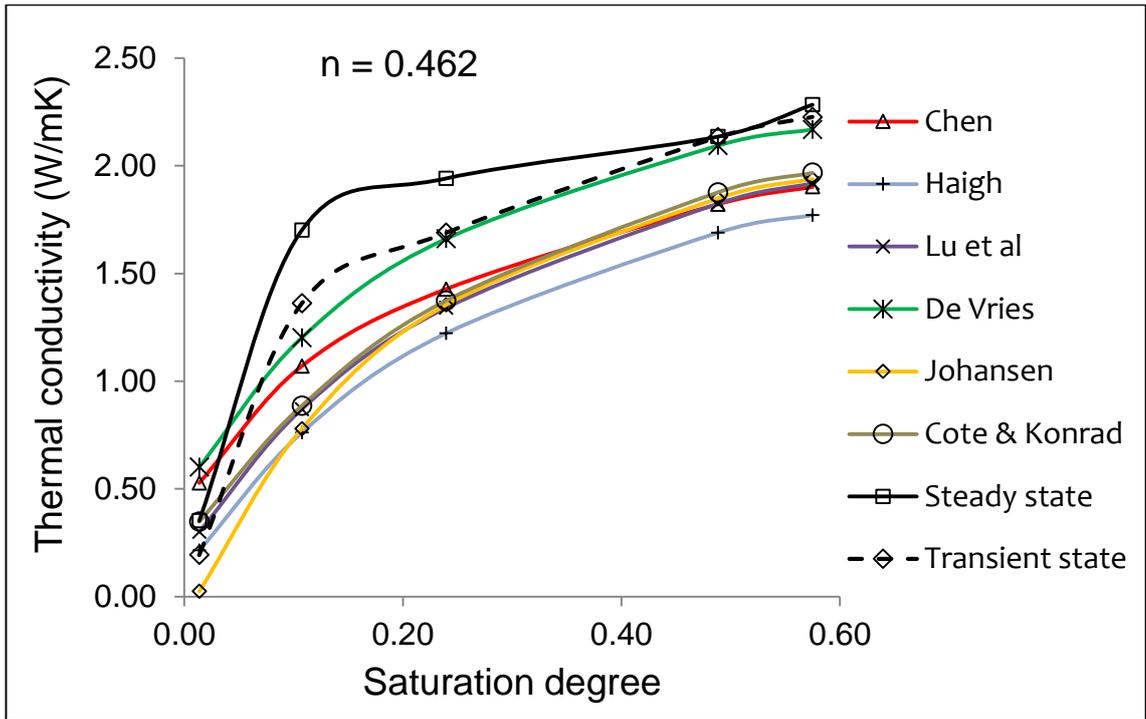


Figure 5-17 : Plot of thermal conductivity versus degree of saturation using different prediction models along with experimental results for Tripoli sand at porosity of 0.462

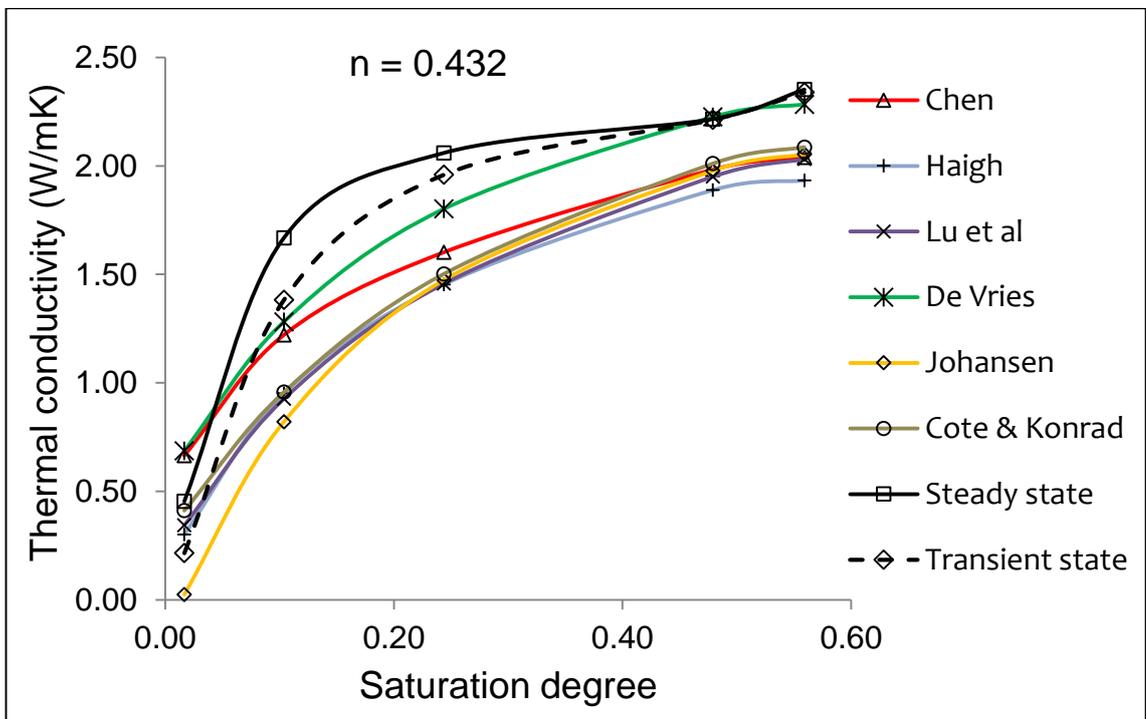


Figure 5-18 : Plot of thermal conductivity versus degree of saturation using different prediction models along with experimental results for Tripoli sand at porosity of 0.432

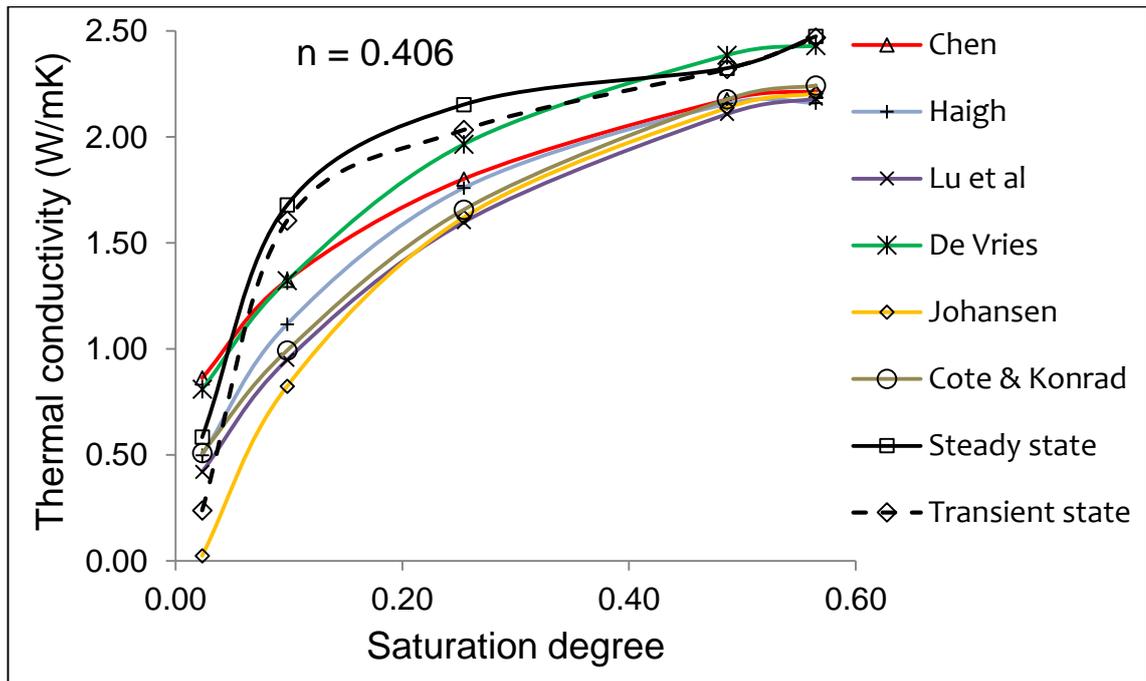


Figure 5-19 : Plot of thermal conductivity versus degree of saturation using different prediction models along with experimental results for Tripoli sand at porosity of 0.406

From these observations, it can be concluded that none of the selected models is able to correctly match the measured thermal conductivity of Tripoli sand at all conditions. It is obvious that some of these models give good predictions in relatively dry conditions and others at high degrees of saturation. One important observation is that most of these models are able to produce better predictions at high saturation and low porosity. This implies that performance increases as the soil approaches a two phase state where conduction plays the dominant role in controlling heat transfer. It is also noticeable that all models relatively failed to estimate the thermal conductivity of such soil at low degrees of saturation, where convection may have become part of the heat transfer process. The calculated thermal conductivity using these prediction methods is compared against the measured values in figures 20 and 21.

The observed discrepancies between the calculated and measured thermal conductivity results can be explained by the fact that most of the presented models were developed from empirical curve-fit datasets for soils with different physical properties. Furthermore, the values quoted for thermal conductivity of the soil particles vary from one model to another.

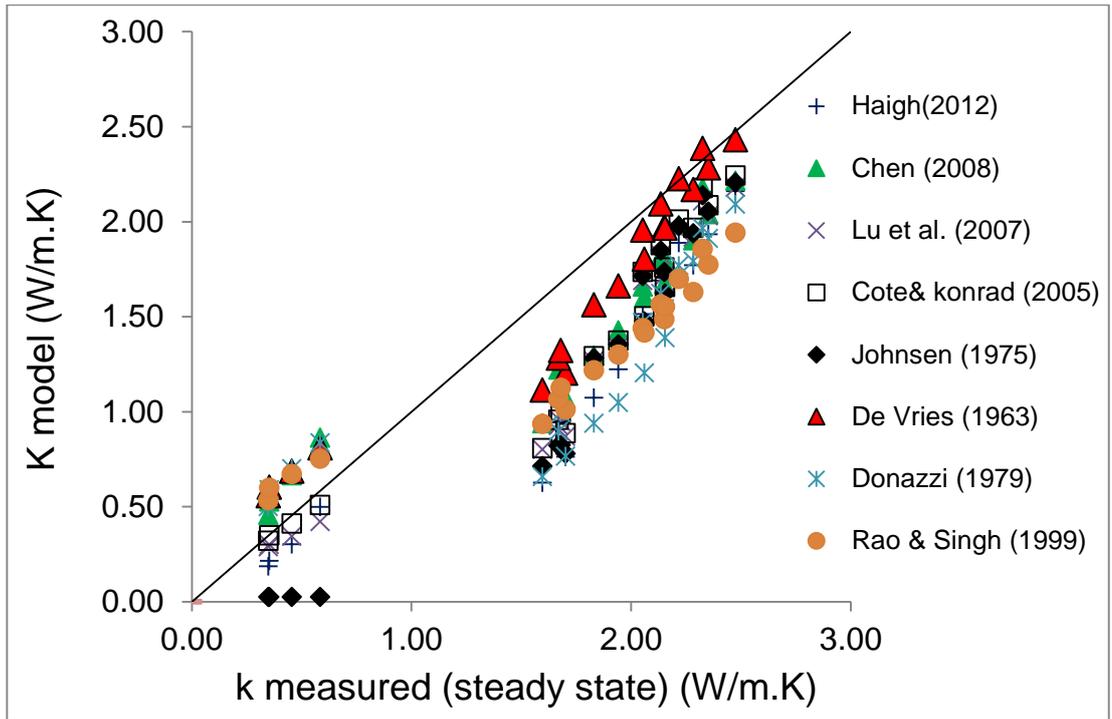


Figure 5-20 : Comparison of predicted methods on measured steady state thermal conductivity results of Tripoli sand

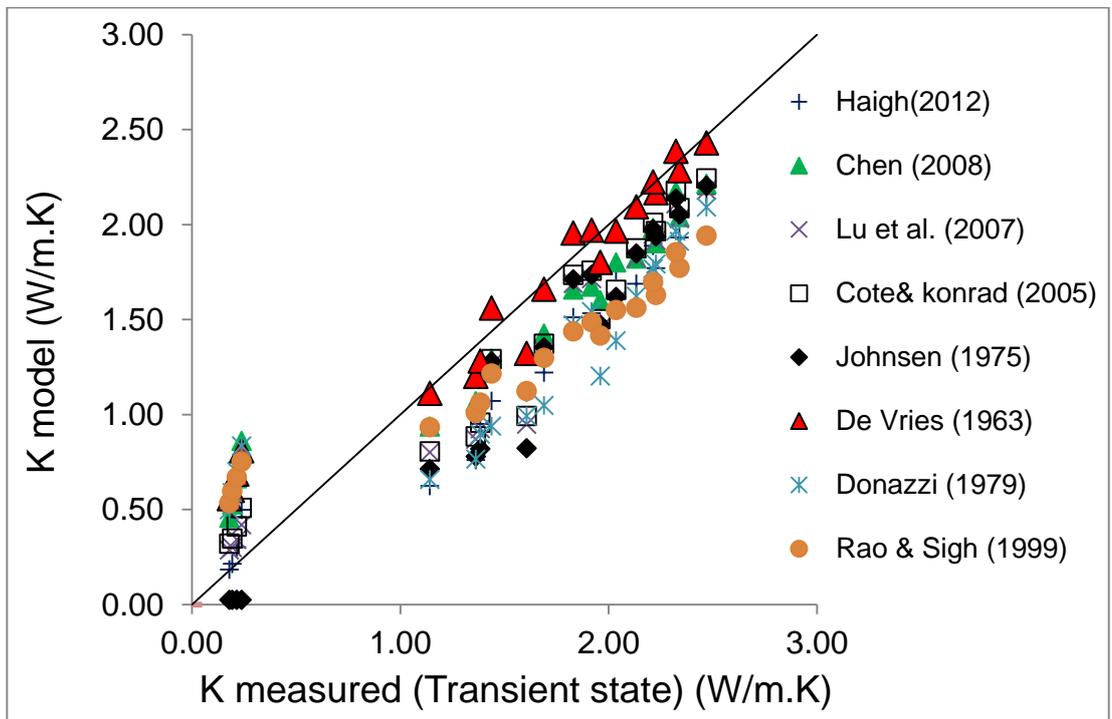


Figure 5-21 : Comparison of predicted methods on measured transient state thermal conductivity results of Tripoli sand

The true thermal conductivity of soil grains will obviously impact on the thermal conductivity of the bulk soil. Finally, most of the experimental results used in the calibration of these models were based on transient methods which provide different values of thermal conductivity when compared with steady state methods. (Midttomme and Roaldset, 1999) mentioned that up to 20% difference between the two methods has been reported in previous studies. The observed overall higher thermal conductivity of Tripoli sand can be related to the existence of the clay (3.52%). Despite of the much lower thermal conductivity of clay soils compared with the quartz grains, at low moisture contents the clay provides more water thermal bridges between the granular skeleton of sand which increases the number of contact point that forms more conductive heat flow paths. Also, the clay expands the surface area that can be covered with water films (Sakaguchi et al., 2007).

5.5.3 Effect of dry density

The overall thermal conductivity of a porous medium can be expressed as the sum of the conductivities related to different heat transfer processes. In dry soils, the thermal conductivity is mainly controlled by the gaseous phase (Huetter et al., 2008). This is because only small areas are in contact between the particles and the remaining bigger part of the particles is in contact with gas molecules. Therefore, most of the heat transfers through gas molecules interaction and gas molecule/particle surface interaction. Thus the thermal conductivity of soils at dry condition has usually low values due to the low thermal conductivity of air. This fact can be observed clearly in figure 5-22 that shows the results of the thermal conductivity versus dry density at different levels of saturation degrees. The observations made from this figure reveal that the thermal conductivity of the Tripoli sand is low at dry condition. Furthermore, the change of thermal conductivity due to the increase of dry density at same level of saturation degree is insignificant. This phenomenon was also observed by Hall and Allinson (2009b). This can be attributed to the less response to the compaction when the soil has the same particle size. Consequently, the number of contact points between soil particles, which the heat passes through, will not increase significantly when compacted. Meanwhile the reduction in the air will not much affect the effective thermal conductivity. It can be noted that the parallel trends of the lines

expressing the thermal conductivity against the dry density in Figure 5-22 indicate the same effect of dry density on the thermal conductivity at all levels of saturation degrees of Tripoli sand.

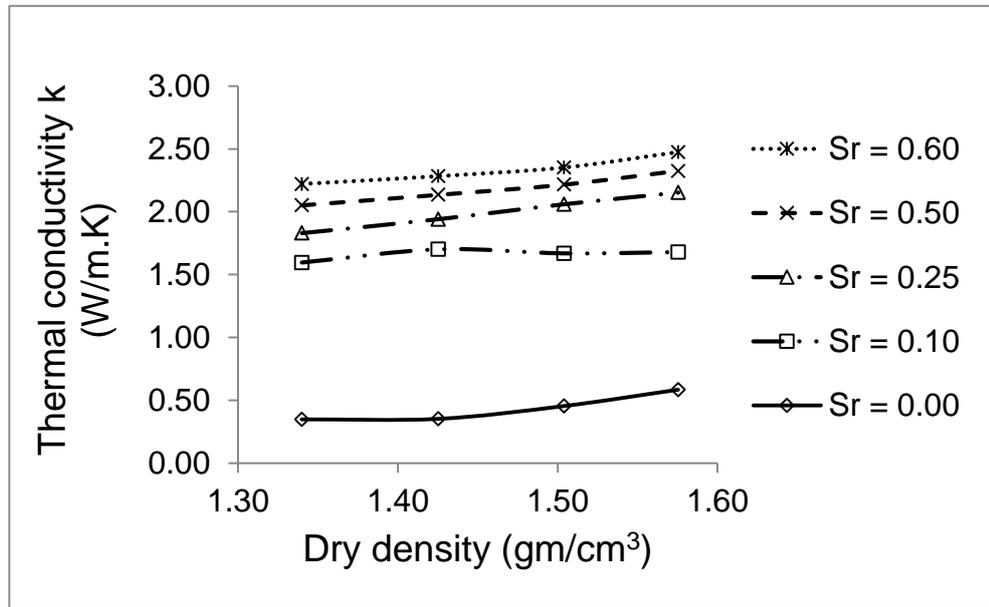


Figure 5-22 : Plot of effective thermal conductivity versus dry density of Tripoli sand at different degrees of saturation

5.5.4 Effect of degree of saturation

For a given porosity (dry density), Figure 5-23 clearly shows that the thermal conductivity increases as the saturation degree increases. However, it can be noticed that this increase rises rapidly at low saturation degree (approximately less than 10%) which means that at low saturation degree the effect of porosity on the thermal conductivity is minor and the major enhancement is due to the water content increase. After that the increase started to decelerate with parallel trends for all levels of porosity and the effect of saturation degree can be considered insignificantly with more influence of porosity started to appear.

The same observation is made when the thermal conductivity results are plotted against the water content (Figure 5-24) where the thermal conductivity at first increases rapidly as the moisture content increases but beyond a certain moisture content (approximately 3%) the rate of the increase become much less. This can be explained as follows: In dry conditions, owing to the thermal conductivity of air being much lower than those of the other soil components, heat transfers only

through contact points between soil particles resulting in a low thermal conductivity.

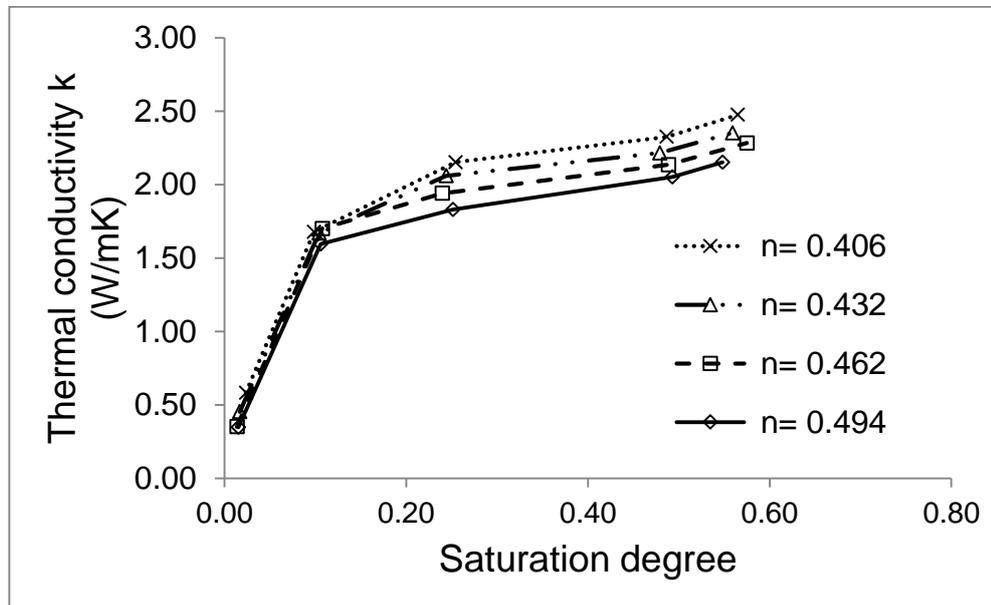


Figure 5-23 : Plot of effective thermal conductivity versus degree of saturation of Tripoli sand at different porosities

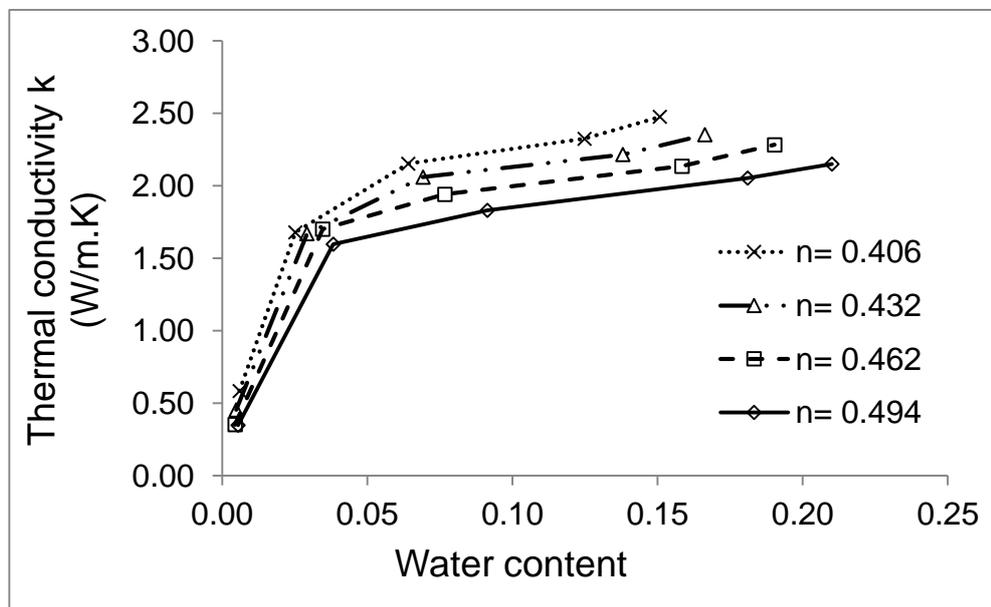


Figure 5-24 : Plot of effective thermal conductivity versus water content of Tripoli sand at different porosities

As the water content increases, more water collects around the contact points and form water bridges between soil grains. As a result, the inter-particle contact within the material is enhanced by the formation of the water menisci and so

conduction from one grain to another is enhanced (Tarnawski et al., 2000a; Hall and Allinson, 2009a). This improvement is rapid until the water film covers all the surface of the soil particles. At this point, the transfer of heat arises largely from two mechanisms; one is the heat conduction through the soil solution and air between solid particles (thermal bridges), and the other is the transfer of latent heat. Under a temperature gradient, more water vapor is likely to condense on the water films surrounding the soil particles due to the larger surface area of the water films compared with the surface area of the water bridges. Condensation, conduction and evaporation would take place through both the water films and the water bridges (Sakaguchi et al., 2007). Both heat conduction through the water bridges and the latent heat transferred with the movement of water vapour are the main cause of the rapid enhancement of the thermal conductivity at low water content values. Beyond this point, any enhancement of the thermal conductivity is only related to the replacement of air by water in the pore spaces, resulting in a slower increase in conductivity.

5.6 The proposed empirical model for Tripoli sand

From the above discussion it is clear that none of the selected prediction models can be used effectively in determining of the Tripoli sand thermal conductivity. This leads to develop an empirical equation based on the experimental results that can be used with better acceptable prediction values.

The relation between the thermal conductivity and water content obtained from the experimental results was presented in figure 5-24. It showed that the thermal conductivity of the Tripoli sand can be satisfactorily described as logarithmic function of the water content. Figure 5-25 is an example of this logarithmic relation. This logarithmic function can be fulfilled successfully at all levels of porosity with R^2 values range between 0.9694 and 0.9732. Accordingly, the thermal conductivity of Tripoli sand can be expressed in terms of water content as following:

$$k = a \ln w + b \tag{5.28}$$

where, a and b are empirical values which express the effect of the porosity. Table 5-4 shows these empirical values at different porosities.

n	0.4940	0.4622	0.4325	0.4055
a	0.4821	0.4992	0.5250	0.5691
b	2.9578	3.1660	3.3589	3.6094

Table 5-4 : Values of the empirical parameters (a & b)

Thus these parameters can be expressed as:

$$a = 1.0444 - 1.111n \quad 5.29$$

$$b = 6.5389 - 7.222n \quad 5.30$$

Substituting in equation 5.28 and simplifying we obtain:

$$k = (1 - n)\text{Ln } w - 7.75n + 6.83 \quad 5.31$$

At dry condition ($w = 0.0$), the following linear relation between the effective thermal conductivity and the dry density (ρ_{dry}) can be used:

$$k = 1.025 \rho_{dry} - 1 \quad 5.32$$

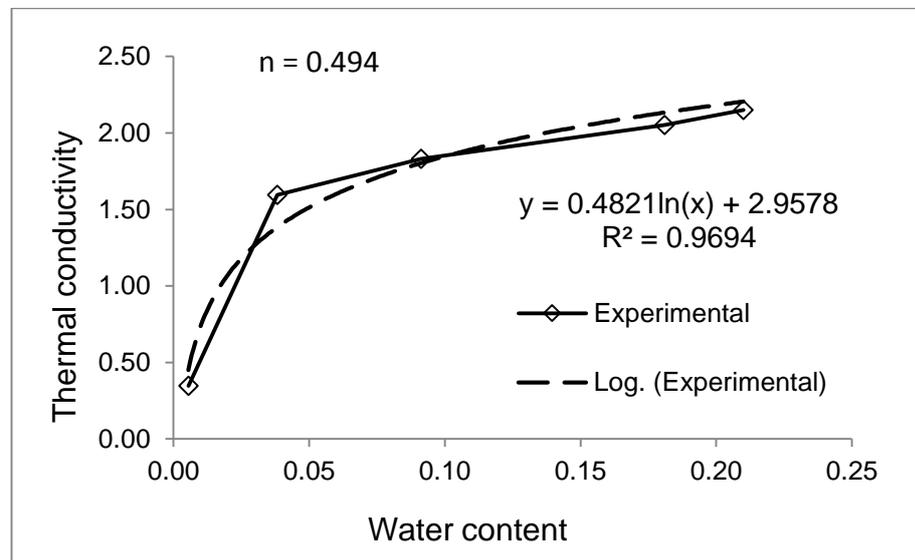


Figure 5-25 : Example of the logarithmic relation between thermal conductivity and water content of Tripoli sand

The calculated thermal conductivity values using equation 5.31 versus the experimental results are presented in Figure 5-26 and the implementation of this

model using different Tripoli sand conditions along with corresponding experimental results are shown in Figure 5-27.

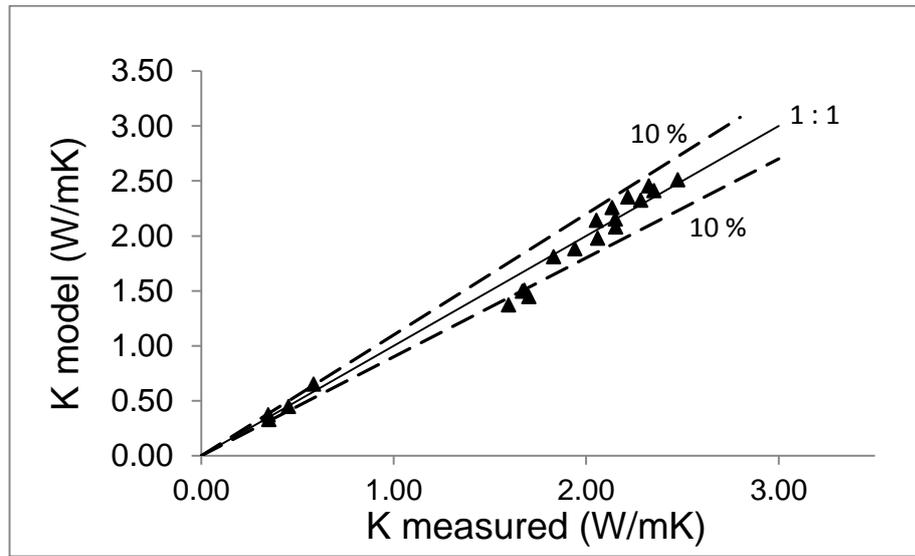


Figure 5-26 : Comparison of proposed model on measured thermal conductivity results of Tripoli sand

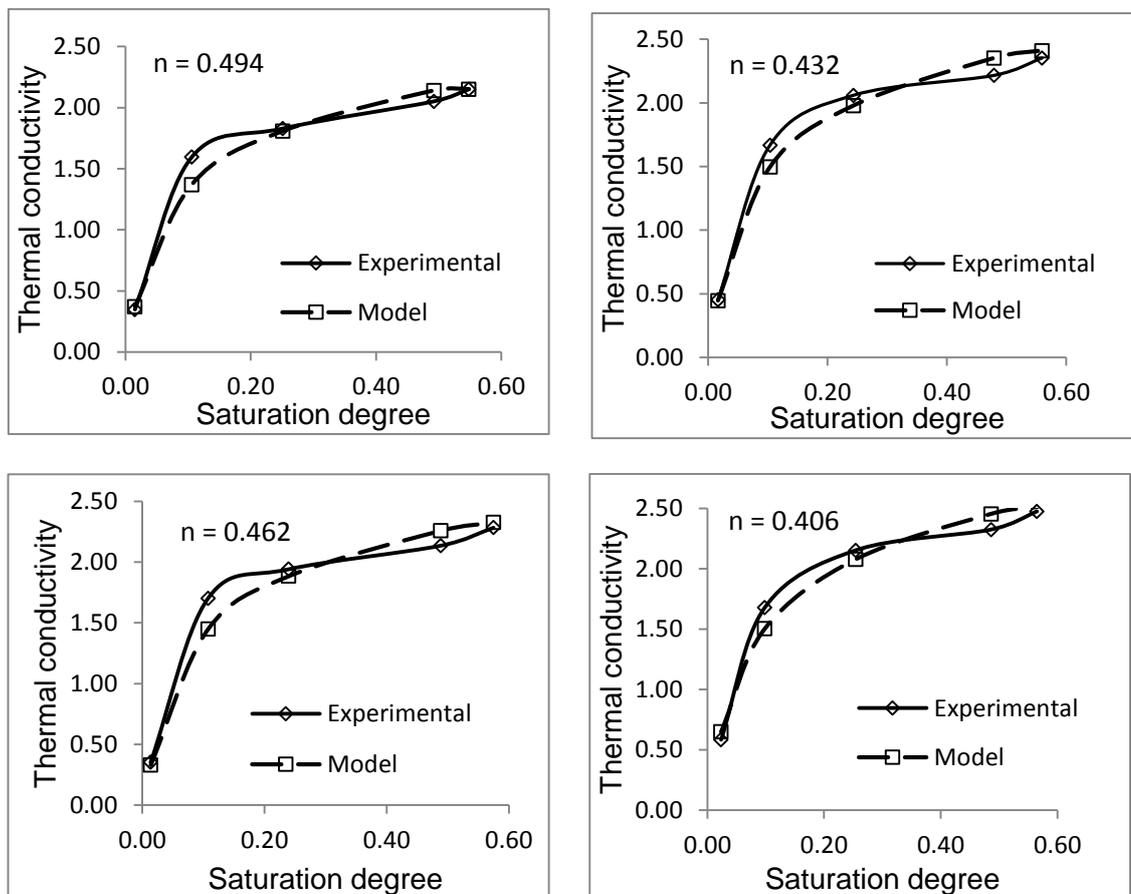


Figure 5-27 : Plots of thermal conductivity versus degree of saturation using the proposed model along with experimental results for Tripoli sand

From these figures, it is clear that this model can provide sensible values of thermal conductivity at any condition with average variation from experimental results equal to 5.7%.

5.7 Summary

The work done in this chapter can be considered as an application of the new steady state thermal cell in the estimation of the thermal conductivity of soils. It presented results of an experimental program carried out on sandy soil (Tripoli sand) aiming to investigate the thermal behavior of this particular soil under different porosities and saturation degrees. Also, since the material used in the experimental work has not been previously thermally tested, this work can be also considered as a case study. Tripoli sand is classified as fine sand with approximately 94% of its mineralogical composition as quartz.

The thermal conductivity has been measured using a new steady state apparatus (divided bar method) and using transient method (single probe method). The experimental testing program was designed to ensure high performance in controlling all boundary conditions and to allow good result interpretations.

The comparison between the thermal conductivity results obtained by the two methods showed similar results at high degrees of saturation especially at low porosities. However, at dry and partially saturated conditions, the probe method gives lower values mainly due to the contact resistance between the probe and the soil particles. Thus the steady state results have been considered and adopted for Tripoli sand.

The effects of the porosity and saturation degree on the thermal conductivity of Tripoli sand were investigated. The results of twenty experimental tests showed that the effect of the saturation degree is significant compared with the effect of dry density especially at saturation degree less than 10%. Also, the results revealed the thermal conductivity is approximately linearly proportional to the dry density at all levels of saturations.

The validation of some existing selected prediction models showed that none of the selected models is able to correctly match the thermal conductivity of Tripoli sand at all conditions. However, some models were more accurate than others in certain conditions. It is also concluded that all presenting models relatively failed

to estimate the thermal conductivity of such soil in low partially saturated condition where the convection started to play roles in the heat transfer mode.

The variation of the thermal conductivity of Tripoli sand can be fittingly described as logarithmic function of the water content at all levels of porosity with R^2 value ranges between 0.9694 and 0.9732. As a result, an empirical model based on the experimental results expressing the thermal conductivity of such soil in terms of water content and porosity has been obtained and validated.

Chapter 6 : Conclusions and recommendations

Exploitation of thermogeology energy in heating and cooling of buildings starts to spread worldwide as an alternative clean source of heat energy. Because these applications require design values of thermal properties of all related materials, the accurate thermal properties of soils are crucial for any underground projects that involve thermo-active processes. This research was a part of study related to the use of the ground as a source and storage of thermal energy by means of GSHP systems. The work has been divided into three main parts.

The first part was focussed on the steady state laboratory technique used to determine the thermal conductivity of soils. It involved the design and construction of a new thermal cell for measuring thermal conductivity of different types of soils under different conditions. This part of research highlighted the necessity to go back over the accuracy of the measurements of the ground thermal properties, mainly thermal conductivity, used in the design of GSHP systems. The accurate values of these parameters will allow to minimize the factor of safety used in the design of such systems.

The second part was to produce a new thermal grout that can be used as a backfill material for borehole heat exchangers. The target was to utilise some low cost industrial and domestic materials (PFA and ground glass) as a thermal grout by mixing them with other material having higher thermal conductivity such as sand and/or fluorspar. This can open up the use of such materials for more useful things than were applied before. In addition to the low cost of used material, the higher thermal conductivity of the obtained grout certainly improves the efficiency of the borehole heat exchangers in transferring of the heat from the ground to the heat carrier.

The better estimation of the thermal conductivity of the soils, obtained from the first part of the research, along with the improvement of the performance of the borehole heat exchangers, obtained from the second part of the research, improve the overall efficiency of the GSHP systems. In other words, the

optimization of the ground heat transfer by improving the design and increasing the grout thermal conductivity allows for reduction in the size of the ground-loop heat exchanger and can result in a considerable cost saving in the total cost of installation

The final part was a case study carried out to measure the thermal conductivity of sandy soils that has not been previously thermally tested (Tripoli sand). The work aimed to study the effect of some physical properties on thermal conductivity of such soils and to produce an empirical model that can be used to predict the thermal conductivity of Tripoli sand under different conditions. The following sections provide a summary of conclusions for each topic obtained during the course of the experimental programme carried out in this research study.

6.1 The new steady state thermal cell

- The design was based on the application of Fourier's law of one-dimensional heat conduction under steady state condition. The new apparatus uses the principle of generating a thermal gradient through a cylindrical soil specimen parallel to the longitudinal axes. The designed thermal cell can be used for soil specimens obtained from routine site investigation (typically U100 samples) as well as reconstituted specimens. Furthermore, using the same principles, similar configurations can be produced for other types of samples taking into consideration the relative proportion between length and diameter of the specimens. Each part of the cell was designed appropriately to optimize the performance of the apparatus. Sample preparations and the test procedures were designed to cover both field and reconstituted specimens with simplicity, high level of accuracy and a high degree of control of boundary conditions.
- The radial heat losses, which occur due to the ambient temperature interface (ATI), can be considered as the main factor that influences the applications of one-directional heat flow methods in the measurement of thermal conductivity of soils. By introducing the concept of a thermal jacket, the analysis of the heat flow showed that the longitudinal heat flow can be maximized and the radial heat flow can be minimized when the thermal jacket was used at an appropriate temperature. Also, it was found that the ideal condition can be

achieved when the thermal jacket temperature is equal to the average between ambient and specimen temperatures.

- It has been concluded that the necessity of using the thermal jacket mainly depends on the temperature gradient along the specimen length as well as the difference in temperature between the ambient and the specimen. As these two parameters are kept very low, the effect of the thermal jacket can be insignificant. In contrast, a high gradient makes the rate of the radial losses vary significantly along the length of the specimen. In this case, the thermal jacket can minimize the radial losses as it works as a heat barrier. However, in all cases using a thermal jacket with temperature near the minimum specimen temperature will be optimum.
- The rate of radial heat loss from the specimen varies along the specimen length. Therefore, at least the temperature of three points along the specimen length should be measured to evaluate the state of the radial heat loss. If any radial loss is noticed, the relationship between the measured thermal conductivity versus the specimen length can be used to correct the obtained results.
- It has been shown experimentally that the number and the direction of thermocouples can lead to erroneous thermal conductivity results if not appropriately considered. Using longitudinal thermocouples (parallel to the heat flow) can elevate the results by approximately 20% higher than using thermocouples perpendicular to the heat flow. Also, a reduction of 5% has been recorded when one mobile thermocouple was used instead of three fixed thermocouples.
- The temperature of sink discs is very important to ensure the heat flows easily from the specimen to the ambient throughout the sink discs. It is recommended to keep the temperature of the sink discs near ambient temperature during the test period. This requires a proper selection of power input. In fact, the power input selection depends on the heat capacity of the soil specimen and on the desired average sample temperature. Specimens with higher heat capacity require higher power input than specimens with lower heat capacity, to produce the same average specimen temperature. For instance, in order to

get an adequate temperature gradient, the required power input for the saturated sand specimen is approximately twice that for the dry specimen at the same dry density. Also, it has been observed that using air forced convection to improve the heat flow from sink discs to the ambient was not necessary as the difference in the calculated thermal conductivity was less than 1% compared with natural convection situation.

- In a partially saturated soil it is important to maintain the average sample temperature as low as possible in order to avoid any early evaporation of the moisture in the soil pores. On the other hand, dry and saturated soils can be dealt with ignoring this precaution.
- It has been noticed that the time required to reach the steady state condition varies from one condition to another. Moisture content can be considered as the main factor influencing this phenomenon. In general, 6 hours has been recorded as the minimum time required to attain a steady state condition.
- The verification of the results has been checked by measuring the thermal conductivity of paraffin wax that has a value of 0.25 W/m.K . The measured value was 0.29 W/m.K , which is 15.6% greater than the specified value. Also, the margin of error due to the uncertainty of the parameters that used in the thermal conductivity measurements was experimentally tested. The results showed that an error of 5.07% is predictable.
- Comparison of thermal conductivity results obtained by the new steady state apparatus and single probe transient method showed significant difference at dry condition however at saturation same results have been obtained. Also, it has been noticed that at partially saturated conditions the results of the two methods became closer as the degree of saturation and the dry density increase. This was explained due to the contact resistance occurred between the probe and soil grains which lead to erroneous the thermal conductivity when using transient probe methods.
- As a practical application, the new apparatus has been used to measure the thermal conductivity of undisturbed and reconstituted cohesive samples. The results obtained were within the expected range. The sample preparation and

the test procedure for the two different soil conditions highlighted the simplicity of using the new apparatus in measurement of the thermal conductivity of soils.

6.2 Thermal enhancement of PFA- based grout

The purpose of this work was to produce a thermal grout that can be used as a backfill material in borehole heat exchangers using unwanted industrial and domestic materials (PFA and ground glass-low cost) and the commodity fluorspar, all of which have relatively high thermal conductivity.

- It has been experimentally found that the thermal conductivity of PFA blended only with cement (basic grout) was very low. The thermal conductivity of this basic grout was 0.320 and 1.081 $W/m.K$ at dry and saturated conditions respectively.
- It has been noticed that using percentages of PFA higher than 40% by weight in all types of grout decreased the thermal conductivity significantly. Furthermore, higher percentages of PFA needed more cement for the consistency of the grout. Thus, the maximum percentage of the PFA should not exceed 40% by weight. On the other hand and for economic reasons, the lower limit of PFA has been considered as 20% by weight.
- The thermal conductivity of the basic grout has been enhanced significantly when blended with coarse sand. The dry and saturated thermal conductivity of this grout is directly proportional to the percentage of added coarse sand and can reach 0.935 and 2.465 $W/m.K$ respectively. On the other hand, when the basic grout was blended with fine sand, insignificant thermal enhancement has been noticed. The highest values were 0.559 and 1.151 $W/m.K$ at dry and saturated conditions respectively. This highlighted the effect of the particle size of the enhancing material on the thermal conductivity of the grout as the two added materials have the same mineralogical composition but with different particle size.
- Similarly, the thermal conductivity of the basic grout has been enhanced dramatically when blended with fluorspar. The thermal conductivity of such grout can reach 1.577 and 2.875 $W/m.K$ at dry and saturated conditions respectively, which concludes that the enhancement was greater than that achieved using coarse sand. This emphasises to the effect of the mineralogical

composition on the thermal conductivity of the grout as the fluorspar has higher thermal conductivity than quartz.

- The thermal conductivity results of PFA basic grout blended with ground glass at different particle sizes showed that none or negative enhancement have been achieved. The low enhancements that have been achieved in these grouts were due to the low thermal conductivity of the ground glass as it contained low percentage of silica in conjunction with the poor particle size distribution of the mix.
- Since the thermal conductivity of the grout should be equal to or greater than the formations and since the ground thermal conductivity in UK is known to vary between 0.9 to 2.3 $W/m.K$, it has been found that the PFA basic grout blended with a combination of fluorspar and coarse ground glass can give an appropriate thermal grout for the use in borehole heat exchangers. The thermal conductivity of this grout ranged between 1.217 and 1.423 $W/m.K$ and 1.793 and 2.055 $W/m.K$ at dry and saturated conditions, respectively. Besides consisting of a combination of two unwanted materials (PFA and ground glass), it also has an advantage of high dry thermal conductivity compared with other grouts.
- Taking into consideration the PFA percentage limitation (from 20% to 40% by weight), the grout composed of 20 % cement, 30 % PFA, 15 % coarse ground glass and 35 % fluorspar by weight is recommended as the most appropriate. The laboratory thermal conductivity of this grout was 1.283 at dry condition and 1.985 $W/m.K$ at saturation. However, the in-field thermal conductivity is expected to be higher due to compaction caused by the self-weight of the grout column in the borehole, which leads to minimize the voids and increase the thermal conductivity. Additional tests were conducted on this particular grout including shrinkage, permeability and flow. The results indicated that no noticeable shrinkage has been observed after 27 days, the permeability of this grout, using falling head method, was found to be around $2.44 \times 10^{-5} m/s$, which meets the contamination limit, and the flow was found to be around 600 mm at water/cementitious material ratio of 0.460, which exceeded the minimum required criterion (450mm).

- Comparing this grout with some available grouts, the optimized grout formulation has a thermal conductivity better than that of thermally enhanced bentonite (1.46 W/m.K) and two times, or more, higher than that of bentonite and neat cement grouts. Furthermore, the thermal conductivity of the suggested grout drops only to 1.283 W/m.K when dried out whereas the bentonite drops to 0.40 W/m.K and that of thermally enhanced bentonite declines to 0.50 W/m.K . Therefore, this grout is also particularly suited to conditions where drying of the grout may occur.
- The thermal resistance of the borehole is expected to be reduced by 35% compared with high solids bentonite grout and 16% compared with thermally enhanced bentonite. Also, a reduction by 20 to 30% of borehole length accompanied with a reduction of 10% in the first cost installation are expected to be achieved.

6.3 Thermal conductivity of Tripoli sand

This work presented results of an experimental program carried out on sandy soil (Tripoli sand) aiming to investigate the thermal behaviour of such particular soil under different porosities and saturation degrees.

- The thermal conductivity has been measured using a new steady state apparatus (divided bar method) and using transient method (single probe method). The comparison between the thermal conductivity results obtained by the two methods showed similar results at high degrees of saturation especially at low porosities. However, at dry and partially saturated conditions, the probe method gives lower values mainly due to the contact resistance between the probe and the soil particles. Thus the steady state results have been adopted for Tripoli sand.
- The observations made from the relationship between the thermal conductivity and the dry density revealed that the thermal conductivity of Tripoli sand was low at dry condition and ranged between 0.348 to 0.584 W/m.K . Furthermore, it has been observed that the change of dry density has a slight effect on the thermal conductivity and similar influence has been observed at all levels of saturation. Consequently, the thermal conductivity of Tripoli sand at a constant

degree of saturation can be fairly considered equal to the average thermal conductivity obtained at minimum and maximum dry densities.

- The results have shown that the thermal conductivity increased as the degree of saturation increased. However, the increase was significant below a certain level of saturation (10%) and started to decelerate above that level at all porosity values. Also, the experimental results have shown that the variation of the thermal conductivity against the volumetric water content have the same trends and can be closely expressed as a logarithmic functions.
- The validation of eight selected prediction models against the experimental results revealed that none of these models can be used to predict the thermal conductivity of such soil at all conditions fittingly. However, some can provide good agreement at dry or nearly dry condition whereas others agree best at high saturations. It is also notable that most of the prediction models provided better results at low levels of porosities especially for high degree of saturation.
- From the relation between the thermal conductivity and water content, it has been observed that the thermal conductivity of the Tripoli sand can be satisfactorily described as a logarithmic function of the water content. This logarithmic function can be fulfilled successfully at all levels of porosity with R^2 values range between 0.9694 and 0.9732. Thus an empirical equation as a relation between the thermal conductivity, water content and porosity has been obtained. The verification of this empirical equation against experimental results showed sensible values of thermal conductivity of Tripoli sand at any condition have been obtained with an average variation equals to 5.7%.

6.4 Recommendations for further research

Several topics have become apparent through the course of this study. These topics have different subjects however all of them are related to soil thermal conductivity measurements.

- Further investigations are required in developing different configurations of thermal cells using different steady state methods. The evaluation of these methods will help to obtain more accurate thermal conductivity results in order to make further steps to standardize the steady state methods.

- The influence of boundary conditions should be more investigated as it has been shown that they have a great effect on the measured thermal conductivity results obtained. Theoretical and numerical analysis of the effect of boundary conditions can help to evaluate and control the boundary condition when compared with laboratory or field results.
- Comparison between steady state and transient state methods is very important as the two methods have provided different results in measuring thermal conductivity of soils. Accordingly, further research is required by testing the same types of soils using the two methods to investigate and understand the discrepancies between the two methods.
- Another important concern is to find out a reference soil that can be used as a reference material in order to calibrate any thermal apparatus. This requires more investigations on the physical and thermal characteristics of such soil to be used with a high confidence as a reference material.
- As underground thermal structures have started to spread word wide, a new soil classification based on the thermal properties of soils become very important. This requires series of thermal laboratory tests in which the thermal properties of each type of soil can be presented in suitable form.
- The success in using PFA and ground glass as a thermal grout has opened the possibility of using other unwanted materials as thermal grouts which can help reducing the negative environmental impact of such materials.
- Dual function underground structures that can serve as supporting and thermal systems such as thermopiles and thermal walls have a promising future in foundation and building technology. One field of research concerns the materials used in such structures. The possibility of using the PFA based grout or other types of materials instead of commonly used material (concrete) can be a topic of research.
- Further research into the heat transfer in soils at partially saturated conditions is required because at this condition, all modes of heat transfer interfere with each other and affect heat transfer process. Analytical study and numerical modelling of different soil structures at all saturation conditions and comparing

the results with laboratory results can help to understand and predict the thermal properties of soils.

- The validation of many available empirical and semi empirical prediction methods of measuring thermal conductivity of soils were based on results obtained from different laboratory techniques on different types of soil. Revalidation of these models based on results obtained using more sophisticated laboratory equipment is required as many of these models have been done a long time ago.

Publications

Some of the material presented in this thesis has been published elsewhere.

The following two journal publications have been produced based on the work contained within this thesis:

- A. Alrtimi, M. Rouainia, D.A.C. Manning, An improved steady-state apparatus for measuring thermal conductivity of soils, *International Journal of Heat and Mass Transfer*, 72 (2014), pp. 630 – 636
- A. A. Alrtimi, M. Rouainia, D.A.C. Manning, Thermal enhancement of PFA-based grout for geothermal heat exchangers, *Applied Thermal Engineering*, 54 (2) (2013), pp. 559 – 564

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