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Interpretation of in situ and laboratory thermal measurements resulting in accurate thermogeological characterization

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ABSTRACT: Growing worldwide interest in the exploitation of geothermal energy resources has led to a scenario where the technology routinely forms part of building-scale renewable energy feasibility studies. A thorough understanding of site-specific thermogeological parameters is a vital design requirement of such systems and accurate measurement and interpretation of these parameters is necessary in order to inform scientifically rigorous system design. An overview of the theory underlying a number of laboratory and in situ thermal characterization testing methods and the results from a number of testing regimes carried out using the various thermal characterization equipment constructed in University College Dublin are presented. Results from both the laboratory steady-state and non-steady-state thermal analysis systems and the in situ thermal characterization system are shown to provide accurate measurements of soil and rock thermal parameters. In addition, the settlement profiles of a number of the tested materials were investigated in order to gain an insight into this potential drawback of exchanging the backfill material placed around electricity cables to optimize thermal transfer efficiency.

1 INTRODUCTION

Ground source (or ‘shallow geothermal’) heat pump systems may be used to harness low-grade heat from the earth’s sub-surface for supply of space heating and / or cooling and hot water to buildings and structures. Ground source energy may be broadly categorized into ‘open loop’ or ‘closed loop’ systems (Hemmingway and Long, 2011d). Open loop systems involve pumping water from sources such as lakes, ponds and wells, exchanging heat energy either directly or via a heat pump and returning it to either a re-injection well, to a surface discharge system or to a sewer. Closed loop ground source energy systems involve the circulation of a heat-transfer fluid through sub-surface pipes which range in size from single-borehole installations which could be used to supply space heating / cooling and hot water to single family dwellings or a small office, to large multi-borehole installations suitable for heating / cooling of large multi-storey buildings. Closed loop systems may be further categorized as horizontal or vertical. Vertical ground source energy systems consist of pipe loops which are installed in the sub-surface in a vertical orientation – examples include ‘borehole heat exchangers’, where piping is installed in a purpose-drilled borehole and the area between the piping the borehole wall is typically backfilled; and ‘energy piles’ where piping is installed into a buildings structural piles in order to avoid the drilling cost associated with borehole heat exchanger systems (Hemmingway and Long, 2011c). Horizontal ground source energy systems consist of pipe loops which are installed in the sub-surface in a horizontal orientation – examples include ‘horizontal ground loops’ where a trench approximately 1.5 m in depth is dug, pipes are laid and the trench is back-filled; and ‘pond loops’, where pipe loops are in-

stalled at the bottom of a large body of water with which heat is exchanged.

An in-depth understanding of aquifer hydraulic properties is essential for the design of open loop ground source energy systems, while an in-depth understanding of sub-surface thermogeology is essential for the design of closed loop geothermal systems. This paper focuses on closed loop systems and describes a number of test methodologies which may be used in order to evaluate ground thermal properties in the laboratory and in the field. A knowledge gap exists in many countries which do not have well developed geothermal industries, where many established domestic-based consultants and contractors lack the specialist skillsets to design such systems. This paper therefore intends to give readers an understanding of the various pieces of equipment available to carry out thermal characterization and an understanding of the underlying theory which should be carefully applied by geothermal project consultants in order to ensure accurate system design. Results from a number of tests are also summarized and compared against values which would have been expected from a review available literature.

2 GROUND THERMAL ANALYSIS

Heat transfer may occur in one of three ways: conduction, convection or radiation. Conduction is generally the most important of these three heat transfer modes when considering a closed loop ground source energy system. Convective heat transfer effects may have to be considered in cases where a significant groundwater flow across a borehole field is present, but in the majority of cases significant groundwater flow is not present and the heat transfer process is dominated by heat conduction

(Wang et al., 2009). The effects of radiation may be ignored in the case of a vertical closed loop system.

Accurate measurement of the thermal properties of both the borehole backfill material and the surrounding soil or rock must be made to inform the design of ground source energy systems so that the appropriate balance between initial capital expenditure and long-term system efficiency can be achieved. Thermal analysis of ground materials may be performed in the laboratory or in the field and the following sections outline a number of different techniques available.

2.1 Laboratory Thermal Analysis

Laboratory thermal conductivity analysis may be performed using either steady-state or non steady-state (transient) techniques (Hemmingway and Long, 2011b). Steady-state analysis refers to a technique whereby a material has a constant temperature with respect to time at any point and the heat flux through the material is constant when subjected to a constant temperature gradient. Non steady-state analysis refers to a technique whereby measurements are taken during the process of heating up a material, following which the thermal conductivity is evaluated and therefore the measurements are recorded and analyzed as a function of time. Thermal analysis carried out using non steady-state techniques is typically faster than steady-state techniques because there is no requirement to wait for steady state conditions in order to take measurements, however the mathematical analysis of the measured data is typically more complex.

The authors have developed systems to evaluate thermal conductivity using both steady-state and non steady-state techniques in the laboratory of the School of Civil, Structural & Environmental Engineering of University College Dublin (UCD), Ireland.

2.1.1 Steady-State Laboratory Analysis

The UCD steady-state thermal analysis system was developed as part of a final year Bachelor of Engineering project in 2011 under the guidance of the authors and is shown in Figure 1.

The initial concept from which the system was designed and constructed was based on Clarke et al. (2008) – a number of design alterations were made during the design and construction of the UCD system which is shown in Figure 2. The UCD steady-state thermal analysis system briefly consists of: a thermally insulated base (which minimizes downward heat flow) underlying a cylindrical aluminum base containing a cartridge heater of known electrical rating. The aluminum base sits on top of the thermal insulation, and is surrounded by an insulated mould (which minimizes radial heat flow) into which a test material is inserted. The design by

Clarke et al. (2008) shows four thermocouples embedded into the test sample, however in the UCD apparatus two thermocouples are typically embedded into the sample at known vertical separation prior to testing.

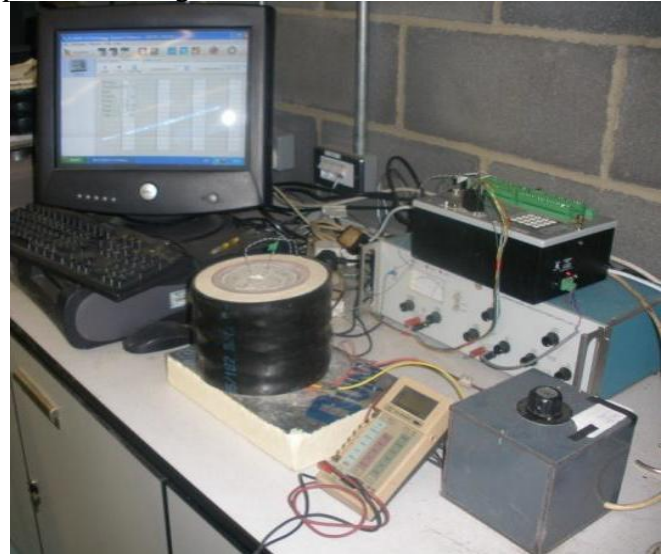


Figure 1. UCD Steady-State Thermal Analysis System

Although two thermocouples are used in the tests described in Section three of this paper, additional thermocouples can simply be embedded into the sample of required.

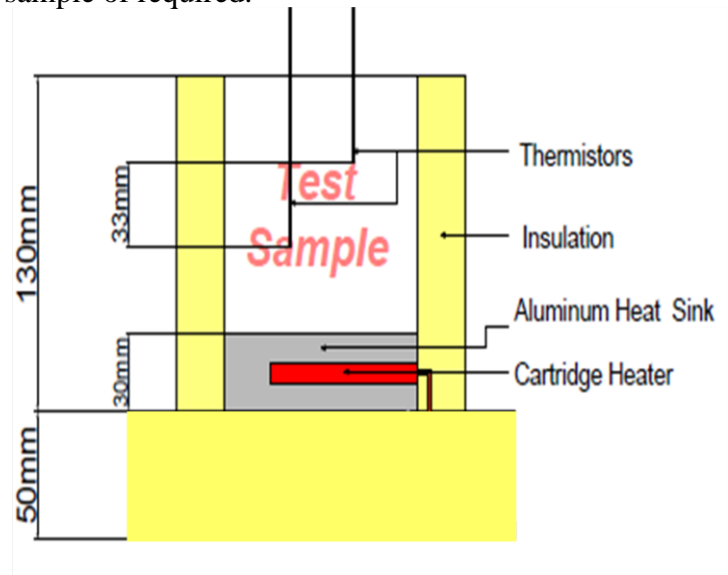


Figure 2. Initial Concept for UCD Design.

The theory underlying steady-state analysis is that of Fourier's law of heat conduction, which states that the temperature gradient created by conduction is inversely proportional to the thermal conductivity for a given heat flow (Midttomme and Roaldset, 1999). This relationship is described in Equation 1.

$$q = -\lambda (dT/dz) \quad (1)$$

where q is the heat flow (W/m^2), λ is thermal conductivity (W/mK) and dT/dz is temperature gradient. Equation 1 may be re-written as Equation 2 by rearranging and replacing q with Q/A , where Q is the

applied heat flux (W) and A is the cross sectional area of the sample under consideration (m²).

$$\lambda = Q \cdot dz / A \cdot dT \quad (2)$$

The thermal conductivity of a sample may thus be evaluated using Equation 2 using the UCD steady-state system as the applied constant heat flux (Q) is measured, the vertical distance between the thermocouples (dz) is known, the cross sectional area of the sample is known and the difference in temperature (dT) between the thermocouples can be recorded during a test. Radial heat loss through the insulated mould and axial heat loss through the base during a test is quantified and considered in order to ensure an accurate value of applied heat flux (Q) is used in Equation 2.

The thermal conductivity of a number of concrete and grout mixes were analyzed using the previously described steady-state thermal analysis system in order to investigate the effect of varying the water-cement (w-c) ratio, aggregate type, sand-cement (s-c) ratio and aggregate proportions on the thermal conductivity. The effect of varying the foregoing parameters on compressive strength of the test mixes was also investigated in parallel to the thermal analysis so that any potential trade-off between mix strength and the variation of the mix constituents required to optimize the thermal properties could be understood.

Although the tests described in the previous paragraph were initially conceived with the intention to investigate the variation of thermal conductivity and compressive strength backfill materials on the performance of borehole heat exchanger and energy foundation applications (i.e. ground source heat pump / geothermal applications), the thermal parameters of a number of additional materials were also investigated and evaluated in the context of the thermal behavior of backfill materials placed around electricity transmission cables. High voltage underground electricity cables produce heat due to electrical resistance in the cables. One of the primary functions of the backfill material placed around electricity transmission cables is to transfer this heat into the surrounding soil at a fast enough rate so as to avoid over-heating, and potential failure of the cables. In some cases, heating of the backfill has induced a degree of settlement, due to drying out of the soil. The backfill materials investigated include a commercially available thermal backfill which is purpose-manufactured for placement around electricity transmission cables, and a number of other materials which are commonly used as backfill materials in the industry – sands of varying moisture content and cement stabilized sand.

2.1.2 Non Steady-State Laboratory Analysis

The UCD non steady-state thermal analysis system was developed by the first author for use in the

laboratory and is shown in Figure 3. The system consists of a linear heat source which incorporates a temperature measuring thermocouple to measure the variation of temperature at a point along the line. Performing a test using the system involves insertion of the ‘thermal probe’ into the sample by either pushing or pre-drilling, applying a known heat energy to the sample for a pre-defined time period and measuring the time series temperature data during this heating cycle. The thermal conductivity is then determined by analysis of the time series temperature data during the heating cycle.

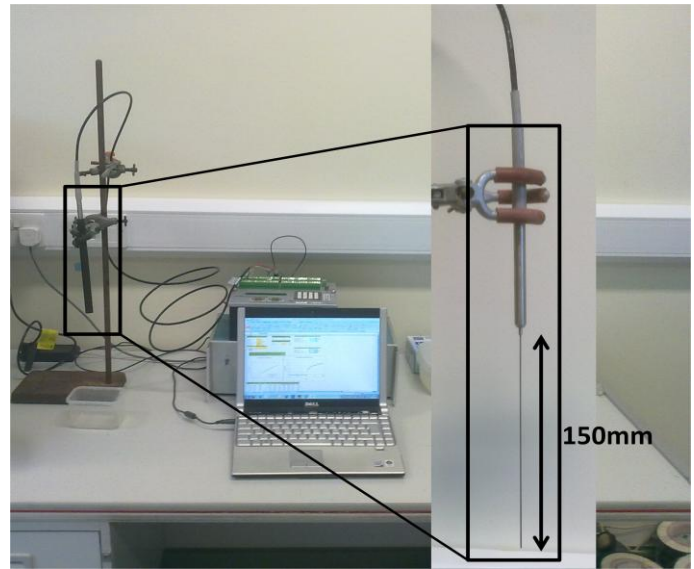


Figure 3. UCD Non Steady-State Thermal Analysis System

The data may be analysed in a number of ways (American Society of Testing and Materials, 2008) such as (i) a non-linear least squares inversion technique or (ii) a so called ‘simplified method’. The non-linear least squares inversion technique involves solving Equation 3, where the inversion technique is required because λ and D cannot be solved explicitly in this equation.

$$\Delta T = -q/4\pi\lambda E_i(-r^2/4Dt) \quad 0 < t \leq t_1 \quad (3)$$

where t is the time from the beginning of heating (s), ΔT is the temperature rise from time zero (K), q is the heat input per unit length of heater (W/m), r is the distance from the heated needle (m), D is thermal diffusivity of the material being analyzed (m²/s), λ is thermal conductivity of the material being analyzed (W/mK), E_i is an exponential integral and t_1 is the total heating time. Note: thermal diffusivity equals thermal conductivity divided by volumetric heat capacity.

A ‘simplified method’ whereby the slope of a straight line representing temperature versus the natural logarithm of time for the heating phase (excluding early data, which cannot be catered for in the mathematics behind the simplified method) of the

test is determined and the thermal conductivity is computed using Equation 4.

$$\lambda = CQ/4\pi S \quad (4)$$

where λ is the thermal conductivity (W/mK), C is a calibration constant defined as the known thermal conductivity of a material divided by the thermal conductivity measured by the thermal probe (which is used to calibrate the accuracy of the probe), q is the heat input per unit length of heater (W/m) and S is the slope of a straight line representing temperature versus the natural logarithm of time for the heating phase.

2.2 In situ thermal analysis

A thermal response test (TRT) is a controlled in situ test during which a known quantity of heat energy is injected into a closed loop heat-exchanger pipe while the heat dissipation rate into the surrounding ground is monitored. Results from a test can be interpreted to determine a number of ground thermal parameters which are vital design requirements for any medium to large scale geothermal system, chiefly the thermal conductivity of the ground formation and the borehole thermal resistance created by the backfill material. Figure 4 shows a sketch of the primary components of the UCD thermal response testing rig (TRT), which was designed and constructed by the first author. In a standard TRT, a heat transfer fluid is circulated in an anti-clockwise direction (from the circulating pump – see Figure 3) through 3kW and 6kW heating elements (differing electrical rating ensures that tests can operate at 3, 6 or 9 kW). The temperature of the circulating fluid entering the vertical borehole heat exchanger ‘Temp Down’ is measured using a thermocouple; the fluid then circulates around a u-shaped borehole heat exchanger and the return temperature ‘Temp Up’ of the fluid is then measured by a second thermocouple. ‘Temp Up’ and ‘Temp Down’ are measured at pre-defined time steps (e.g. 30 second intervals) throughout the period of the test. A full description of the design, construction and performance validation of the UCD thermal response testing rig is available in Hemmingway and Long (2011a).

A number of different methods are available for the analysis of thermal response test data, all of which are based on Fourier’s Law of Heat Conduction (Florides and Kalogirou, 2008). The most commonly used analysis method is known as the ‘analytical line source method’, which adopts the analytical solution for the response to unsteady heat conduction applied to an infinite medium with homogeneous and isotropic properties (Signorelli et al., 2007).

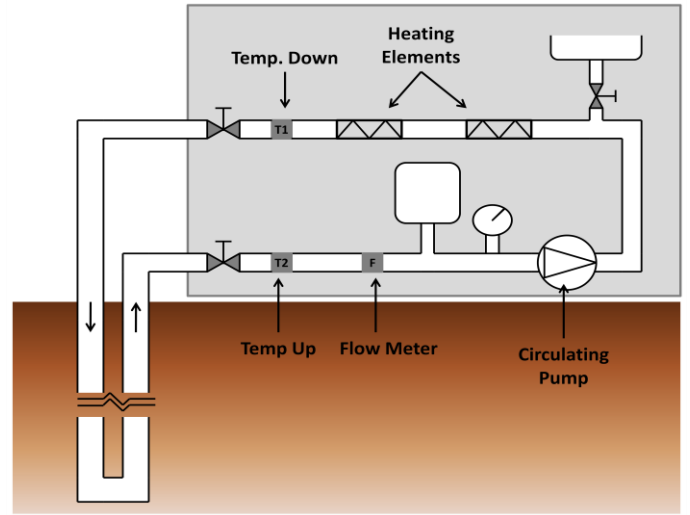


Figure 4. UCD Thermal Response Testing Rig

The effective conductivity of the ground formation into which the heat exchanger is installed may be calculated by plotting a graph of average temperature (i.e. average of injected and return temperatures) against the natural logarithm of time, determining the slope of the linear portion of the graph (k) and entering the results into Equation 5.

$$\lambda = Q/4\pi kH \quad (5)$$

where λ is the thermal conductivity (W/mK), Q is the injected heat power (W) and H is the depth of the borehole heat exchanger (m) being tested

3 ACCURATE CHARACTERIZATION

In a number of international cases, application of the theory explained in Section two of this paper and / or poor site or laboratory testing practices has resulted in incorrect thermal characterization. The following sections describe the results obtained from a number of tests carried out by each of the pieces of equipment described in Section two and compare results against those available in literature.

3.1 Steady State Laboratory Results

A number of concrete mixes (which would be used as the ‘backfill’ in energy pile systems) and a number of grout mixes (which would be used as the ‘backfill’ for vertical borehole heat exchanger systems) were prepared for testing with the steady-state thermal analysis system shown in Figures 1 and 2. Three sets of three concrete mixes were prepared with one distinct parameter varied in each of the three sets for thermal testing, while three sets of six mixes with the same constituents were prepared for compressive strength testing. The aggregate proportions were varied in the first three mixes, the water-cement (w-c) ratio in the second three mixes and the aggregate type in the last three. Two thermocouples

were inserted at a predefined vertical distance from each other (dz in Equation 1) during the casting process. Four grout mixes were prepared for thermal and compressive strength testing in a similar manner. Three of the samples were prepared with variable sand-cement (s-c) ratios alongside one commercially available ‘thermal grout’ which was prepared in-line with the manufacturer’s instructions. Although the grout mixes would not have a load carrying function in practice, their compressive strengths were measured in order to complete the data set. The applied heat flux and cross sectional area, Q and A respectively in Equation 2, were constant at 11.5 W and 0.00739 m² for all samples. The results of the thermal analysis and compressive strength testing are shown in Table 1 and a typical set of results for the variation in thermal conductivity with the water-cement ratio is given on Figure 5.

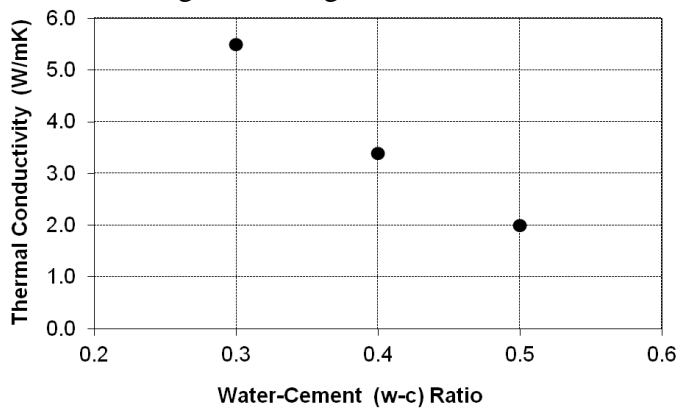


Figure 5. Thermal Conductivity vs. w-c ratio

Midttomme and Rolandset (1998) suggest that thermal conductivity should increase with an increasing coarse aggregate content. Although this is not initially evident when comparing the aggregate-variable samples, it is thought that the value for F/C 30/39 may be erroneous due to possible incorrect insertion of the thermocouples into the mix. If the measured thermal conductivity value for the F/C 30/39 mix is ignored, then the trend suggested by the relevant literature is confirmed, although re-testing would be required in order to confirm this. The compressive strength is not significantly affected by the variation in aggregate size.

A clear relationship is observed in the samples with variable water-cement ratios (Figure 5). Both thermal conductivity and compressive strength decrease significantly with increasing water-cement ratios. Aggregate type is also shown to have a considerable effect on the thermal conductivity of the concrete mix for the two mixes successfully evaluated for thermal conductivity. No clear relationship is evident for the effects of thermal conductivity due to variation of the sand-cement content of the grout mixes. The thermal grout is shown to have a higher thermal conductivity than the standard sand / cement / water grout mixes.

Table 1. Steady-State GSHP Backfill Testing Results*

Variable	Thermal Conductivity (W/mK)	Compressive Strength (MPa)
F/C 20/49	3.4	26.3
F/C 25/44	2.6	25.7
F/C 30/39	3.3	25.1
w-c 0.3	5.5	36.0
w-c 0.4	3.4	30.2
w-c 0.5	2.0	15.9
Limestone	No Result	38.3
Granite	2.3	33.9
Quartzite	2.7	33.6
s-c 2.0	1.1	25.0
s-c 3.0	2.0	20.5
s-c 4.0	1.7	28.0
Thermal Grout	3.2	4.4

* F/C refers to percentage volume of fine / coarse aggregate per mix, w-c refers to water-cement ratio and s-c refers to sand-cement ratio.

In addition to the testing regime investigating the thermal properties and compressive strength of a number of materials which may be utilized in connection with ground source heat pump (geothermal) applications outlined above, a number of tests were also carried out to investigate the thermal and settlement characteristics of materials used for backfilling around electricity transmission cables.

Table 2. Steady-State Cable Backfill Testing Results

Variable	Thermal Conductivity (W/mK)	Settlement (mm)
Wet Sand	3.2	18.4 – 33.0
Commercial	2.4	3.4 – 17.7
CSS	1.8	0.00
Dry Sand	1.3	0.00

Four commonly used cable backfill materials – wet sand (water content 8% by weight), commercially available backfill grout (43% aggregate, 40% aggregate, 5% fly ash, 3% Portland cement and 9% water by weight), cement stabilized sand – CSS (87% sand, 6% Portland cement and 7% water by weight) and dry sand (water content 3.5% by weight) were prepared for testing. The thermal conductivity of each compound was then evaluated using the UCD steady-state thermal analysis system (Figure 1). The heat-induced settlement potential of each sample was measured by application of a line source heat (representing the soil-heating induced by a high voltage electricity transmission cable) to a scaled model of backfill material contained in an 8' long x 8' high x 4' wide test specimen. A static load equivalent to 10 kN/m² was applied to the test specimens prior to heating in order to mimic in situ loading conditions (e.g. potential traffic loading). Table 2 provides a summary of the thermal and settlement testing results.

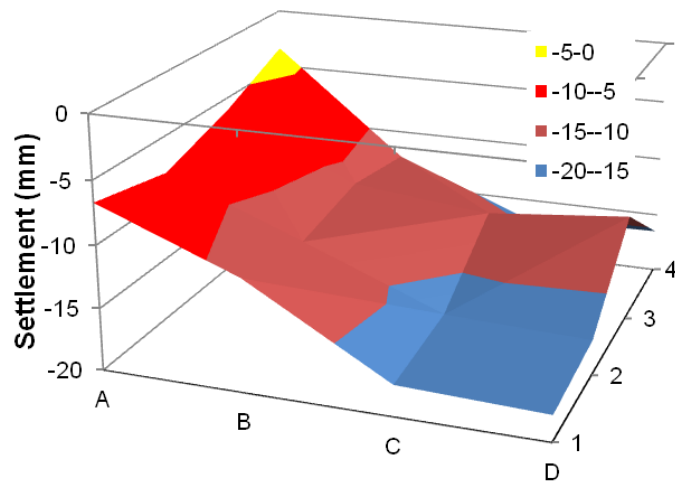


Figure 5. Settlement Profile of Dry Sand

Figure 5 shows the settlement profile observed in the dry sand test specimen, following application the heating load to the loaded scaled down model. A maximum settlement of 17.5 mm was observed at measurement point C-1 of the dry sand. Figure 6 shows the settlement profile observed in the wet sand test specimen. A maximum settlement of 33.0 mm is observed at measurement point D-2 of the wet sand. No settlement was observed in either or the commercial grout or the commercially available backfill material test specimens.

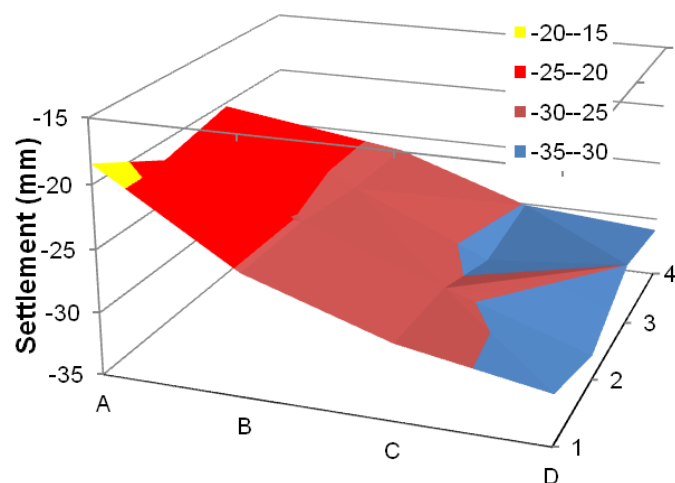


Figure 6. Settlement Profile of Wet Sand

In addition to the settlement observed in the wet and dry sand test specimens, significant drying-out of the sand in the direct vicinity of the linear heat source was observed. This localized drying out of the soil would have the effect of reducing the thermal conductivity of the soil directly surrounding the cables, because water (thermal conductivity 0.6 W/mK) is effectively being replaced with air (thermal conductivity 0.02 W/mK) in the void spaced between sand particles, and would therefore reduce the thermal dissipation efficiency of the backfill material.

3.2 Non Steady-State Laboratory Results

A number of soil samples have been analyzed using the UCD Non steady-state analysis system. Prior to testing the soil samples, the system was used to analyze the thermal conductivity of a number of materials of known conductivity such as water and glycol – the measured results confirmed the accuracy of the system. Comparison of the soil sample thermal measurements against available literature (EED, 2010, Fjeldskaar et al., 2009, Goodrich, 1986) indicates that results obtained were within the expected ranges. Table 3 provides a summary of results measured for a small portion of the tests performed.

Table 3. Non Steady-State Probe Measurement Results*

Soil type	N	Thermal Conductivity (W/mK)		
		Measured (Avg.)	St. Dev.	Expected
Glycerol	2	0.29	0.01	0.29
Silt	5	2.01	0.60	1.0-2.3
Stiff Clay	6	2.12	0.23	0.9-2.2
Peat	4	0.61	0.01	0.2-0.8

* N refers to the number of samples in the data set.

Although the thermal conductivity of a material is influenced by its density, temperature, particle shape, porosity, moisture content and mineral composition (Mattsson et al., 2008), the results shown in Table 3 confirm that each of the measured thermal conductivities are within the range expected for each material type. It should be noted that the ‘expected’ range of thermal conductivity values in Table 3 should not be taken as the absolute limit for the soil types quoted due to the fact that soil is variable by its very nature, and therefore variations in the parameters mentioned earlier in this paragraph will have the effect of varying the thermal conductivity in any given sample. The samples tested under each soil type in Table 3 are characterized based on the authors’ interpretation of soil type based on visual inspection of each sample. The higher standard deviation associated with the silt is due to the fact that the constituents of the silt samples were quite variable (for example, differing sand contents, densities and moisture contents were observed). Thermal analysis of a large range of soil and rock types is ongoing at the Department of Civil, Structural & Environmental Engineering of University College Dublin which will inform the construction of a thermal conductivity database of Irish and UK soil and rock types.

3.3 In Situ Thermal Response Test Results

The UCD thermal response testing rig has been used in order to carry out thermogeological characterization at a number of site locations in Ireland and the United Kingdom. One of the testing regimes carried out is summarized in this section to illustrate the importance of careful and attentive operation of a

thermal response test and correct interpretation of the results from a test. Readers should refer to Hemmingway and Long (2011e) for more details. Ground conditions at the site consisted of made ground from ground level to 1 m below ground level, sand and gravel from 1 m to 21 m below ground level, soft fractured chalk and flint from 21 m to 75 m below ground level and firm chalk and flint beneath 75 m below ground level. U-shaped borehole heat exchanger piping was installed into a borehole to a depth of 201 m below ground level and the borehole backfilled with pea gravel.

Three thermal response tests were carried out consecutively on the installed borehole (denoted TRT 1, TRT 2 and TRT 3 in this paper). The first thermal response test ran for 5.4 hours. The second started 4.5 hours after completion the first and ran for 15.8 hours and the third started 4.5 hours after completion of the second and ran for 6.6 hours.

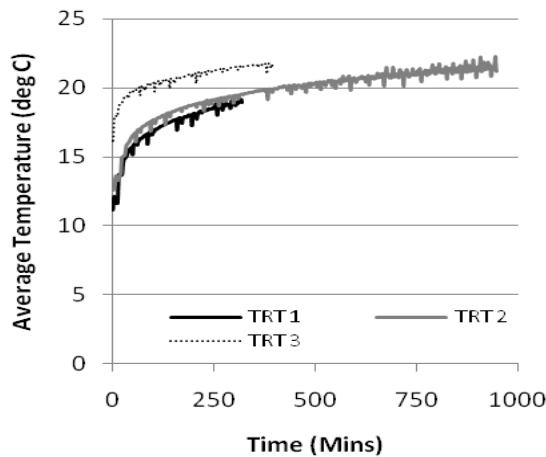


Figure 7. Thermal Response Testing Results

Figure 7 shows a plot of average temperature (i.e. the average of the injected and return borehole heat exchanger temperatures) against time for each of the thermal response tests. Each of the profiles shown are approximately similar in shape, and appear to represent a profile which would be expected for a thermal response test, i.e. a period of transient temperature response where the measurements are influenced primarily by the borehole backfill material, followed by a period of stable heat flow where the temperature development is influenced primarily by the thermal properties of the geological formation into which the borehole heat exchanger is installed. The measurements obtained during TRT 1, TRT 2 and TRT 3 were processed using the analytical line source method, resulting in calculated effective thermal conductivity values of 1.9 W/mK, 2.0 W/mK and 3.0 W/mK respectively. The difference in calculated thermal conductivity values observed in TRT 2 and TRT 3 (in the same borehole, and therefore the same geological formation) occurs due to the thermal elevation imposed on the sub-surface by each of the preceding thermal response tests. This difference in thermal conductivity results is ob-

served despite the fact that each of the profiles observed in Figure 7 represent a shape which would be expected for a thermal response test, and if viewed in isolation, it is likely that an operative analyzing the results of a thermal response test would consider any of TRT 1, TRT 2 or TRT 3 as acceptable. This illustrates the importance of careful performance of thermal response tests and well informed analysis of the resulting data sets. It also shows that in cases where a thermal response test is interrupted (e.g. due to a power failure, a leak etc.), the borehole should be abandoned for a suitable period of time for the geological formation to return to its natural temperature conditions. Hemmingway and Long (2011e) show that the difference in borehole heat exchanger installation cost associated with misinterpretation of thermal conductivity values resulting from TRT 1, TRT 2 and TRT 3 for the project in question is approximately €45,000.

4 CONCLUSIONS

The various different types of closed loop ground source energy systems are summarized in the context of installation requirements and possible applications. An in-depth understanding of aquifer hydraulic properties is essential for the design of open loop ground source energy systems, while an in-depth understanding of sub-surface thermogeology is essential for the design of closed loop geothermal systems.

An overview of the basic theory on which steady-state and non steady-state thermal conductivity laboratory testing and analysis is performed is provided. Two laboratory testing apparatus designed and constructed in University College Dublin are described, alongside a summary of results from a number of testing regimes. Testing using the steady-state analysis system investigates the thermal effects of varying aggregate size, the water-cement ratio, the sand-cement ratio and the aggregate type in a number of concrete and grout mixes – the water-cement ratio and aggregate type are shown to significantly affect the thermal properties of the samples. The effect on the compressive strength of the various samples is also investigated. The results from a number of non steady-state thermal analysis tests are also presented. Thermal conductivity results from measurements performed on glycol, silt, stiff clay and peat samples are shown to fall within the ranges expected.

Investigation of the thermal conductivity and settlement characteristics of a number of materials in the context of the thermal behavior of backfill materials placed around electricity transmission cables was also carried out. The thermal conductivity measurements are found to fall within the expected ranges, and the settlement observed in both the wet

and dry sand sample raise questions as to the suitability of sand as a material for backfilling around high voltage electricity transmission cables.

A description of the UCD thermal response testing rig alongside a summary of the relevant theory is presented. The results from three consecutive thermal response tests carried out on a single borehole are presented. Thermal conductivity values of 1.9 W/mK, 2.0 W/mK and 3.0 W/mK are observed in each of the respective tests. This illustrates the importance careful performance of thermal response tests and well-informed analysis of the resulting data sets.

4.1 Acknowledgements

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