Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

New Methods for Determining the Thermophysical and Hydraulical Properties of Unsaturated and Unconsolidated Rocks

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Keywords: unconsolidated rocks, thermal conductivity, thermal diffusivity, hydraulic conductivity, water retention function

ABSTRACT

The heat conductivity and diffusivity as well as the hydraulic properties of unconsolidated rocks are important parameters to quantify the conductive and convective heat transfer in the subsurface. Depending on the type and way of installation of an underground heat exchanger system the involved soil undergoes compaction, change in saturation e.g.. The most soil properties will be changed somehow, just the grain size distribution remains constant.

In the operation phase the temperature and saturation are variable in time and space. The change in the ratios of the gas phase and water phase in the subsoil affects the themo-physical performance. The hydraulic conductivity of soils is a non-linear function on the water content. The heat capacity of unconsolidated rocks can be calculated from the heat capacities of the individual components and their volume fractions. In contrast, there is no linear dependence of the thermal conductivity and the water content. Established computational models provide approximations for the thermal conductivity as a function of water content and other constraints such as temperature.

However, for the additional determination of convective transport behavior, the unsaturated hydraulic conductivity and water retention function, largely dependent on the tortuosity of the pore space, have to be determined simultaneously. Here, for the integrated study of soil mechanics, hydraulic and geothermal properties of unconsolidated rocks, a heat and temperature conductivity meter has been developed and patented. The device allows measurements of samples either under constant pressure of up to 7.6 Mpa which means soil compaction can be varied stepwise or it can be driven at a constant sample volume. The treatment temperatures of the soil samples can be varied from -10 to +80 ° C. Additionally to the parameters such as temperature, pressure, volume and water content, the capillary tension is recorded during the measurement.

For the simultaneous study of water transport characteristics and the unsaturated conductivity of undisturbed unconsolidated rock samples, an evaporation test has been developed. It is equipped with a full-space line source to determine the thermal conductivity. This allows the simultaneous measurement of thermal conductivity, water retention characteristics and hydraulic conductivity of a soil sample up to the air entry point of the ceramic tensiometer cap (approx. -780 hPa).

The functionality of the equipment and methods has been validated and the devices were used for soil investigation in numerous projects. Determination of the design parameters of shallow geothermal systems and of the heat transfer of burried cables is thepurpose of the methods presented in this study. The data compile mathematical models for the thermo-physical parameters of soils. A mathematical function for calculating the thermal conductivity in dependence of the capillary tension is introduced here and the test results of geotechnical and geothermal soil parameters of sand, clay and silt are presented.

1. INTRODUCTION

1.1 Principles of heat transfer in soils

Subsurface heat transfer is composed of several mechanisms. In areas of moderate climate the dominant mechanisms are convective and conductive heat transfer. Their relative proportion depends on the in-situ conditions. The third type of heat transfer, namely radiation may be neglected since it represents less than 1% of the total energy transport. On sites with sufficient subsurface temperatures to allow a phase transition of water from liquid to vapor, heat transfer through vapor diffusion also occurs. Vapor diffusion accounts for 40 - 60% of total heat transfer in the top 2 cm of a soil profile (Koorevaar et. al. 1983). The factors influencing the transfer of heat in unconsolidated rocks are shown in table 1.

Table 1: Physical parameters and processes controlling heat transport in a three-phase soil system (extended after Hartge & Horn 1999)

Parameters and processes			
Solids	**Liquids**		**Gases**
Conduction	**Conduction**	**Convection**	**Convection**
Minerals	Dissolved solids	Rate of infiltration	Vapor diffusion
Surface area	Flow-through area	k/ψ relationship	pf/wc relationship
Grain size	pf/wc relationship	pf/wc relationship	Evaporation
Structure	Temperature		Condensation
Bulk density			Water inclusions
Number of contacts			Temperature
Temperature			

The heat capacity of unconsolidated rocks can be calculated from the heat capacities of the individual components and their fractions by volume. In contrast there is no linear dependence between thermal conductivity and water content. Established computational models (table 2) provide approximations for the thermal conductivity as a function of water content and other constraints such as temperature. However, to determine the convective heat transport behavior, the unsaturated hydraulic conductivity and water retention function, largely dependent on the tortuosity of the pore space, have to be determined simultaneously.

Table 2: Functions for the calculation of the thermal conductivity of unconsolidated rocks depending on various parameters.

Year	Author	Parameter
1949	Kersten	Water content, dry density, grain size
1963	De Vries	+ Organic material, minerals, grain geometry
1975	Johansen	No new parameters
2005	Cote & Conrad	No new parameters
2007	Lu et al.	+ Temperature

2. SOIL PARAMETER ACQUISITION FOR GEOTHERMAL PLANT DESIGNS

2.1 General

A comprehensive geothermal soil characterization requires the determination of many parameters. Therefore a combination of different methods and devices is necessary. The measurement equipment must allow to determine and calculate the thermal conductivity and thermal diffusivity as functions of:

- water content and it`s variability,
- capillary tension,
- dry bulk density and pore space,
- confining pressure,
- in-situ temperature and future operational temperature,
- heat flow direction.

The design of a specific geothermal system may not require the measurement of all these parameters. Therefore it was the aim to develop instruments which are well suited for the determination of the relevant parameters for common geothermal systems. A second application of the presented methods is the parameter acquisition of soils for installation of buried power cables.

2.2 Offshore power cables

International agreements do not allow to disturb the underground temperature by more than two Kelvins in submarine soils surrounding a cable. With the current state of knowledge such temperature gradient avoids negative impact on the benthic biocoenosis. Therefore the investigation of thermal properties is done in dependence of the soil compaction, because the compaction can be varied by the choice of construction method and the depth of the cable. A variation of the water content in the laboratory tests is not of interest because the soil in the seabed is saturated.

2.3 Borehole heat exchangers

In addition to the saturated thermal conductivity the quantification of the hydraulic permeability is important. Depending on the hydraulic boundary conditions, a large proportion of the whole heat transport around geothermal probes can be done by the groundwater convectively. In the relevant depths no soil compression work is performed, so investigating various soil-compressions in not necessary. In addition to the in-situ soil properties a measurement of the heat transfer resistances between soil and backfill material of the probes is important. (Schmid, 2005)

2.4 Onshore power cables

Onshore power cable can be classified into cables of the power distribution network having an electrical voltage level ranging from 400 up to 20,000 Volts and cables of the transmission system for electricity having a voltage range of from 20,000 volts to 400,000 volts.

Cables of the transmission system are usually laid at depths from 1.20 to 1.60 m b. g. s.. At this depth, the daily variations in surface temperatures as well as short-term hydraulic changes due to precipitation events are hardly recognizable. The phase shift of the temperatures at this depth to the surface temperatures is more than one month (Scheffer/Schachtschabel 2002, after Schmidt & Leist in Geiger, 1961). Power cables of this voltage level are often incorporated into thermally improved beddings based on cement or bentonite binders. They guarantee good thermal properties even in the dry state. The maximum tolerable temperature of 70°C at the cable jacket will be transferred into the embeding or grout material in the trench. The operation of cable creates a temperature gradient within the surrounding soil of the cable trench. A highly conductive construciton material in trench reduces this gradient which minimizes dry outs in the surrounding soil. Capacitiy losses of the cables due to overheating can be avoided by applying highly conducitve grouts.

The cables of the distribution network are mostly laid at depths of 60 to 80 cm. At such depths, the short-term hydraulic changes due to precipitation events act very fast and changes in the surface temperatures are recognizable with a phase shift of more than 12 hours. (Scheffer/Schachtschabel 2002, after Miess 1968) The geothermal investigation of soils in the area of cables of the transmission system must be carried out in dependence of the compression. The capillary tension and the temperature of the soil need to be considered as well. (Stegner et. al., 2013)

2.5 Horizontal geothermal heat collectors

The investigation program for geothermal collectors should be structured similar to the program for onshore power cables of the distribution network. Because of the low temperature gradients during plant operation, the temperature-dependent studies are typically not necessary. However, the possibility of ground freezing has to be considered.

3. UNCONSOLIDATED ROCK THERMAL CONDUCTIVITY METER

The new thermal conductivity and diffusivity meter presented in this study is feasible for the integrated study of soil mechanical, hydraulical and geothermal properties of unconsolidated rocks (EP13159234.7 and EP11757191.9). The device allows measurements of samples either under constant pressure of up to 7.6 MPa or at constant volume. The temperature of a sample can be adjusted from -10 to +80 °C. The sample can be measured under varying water content. Additionally to the parameters temperature, pressure, volume, and water content, the capillary tension is also recorded during the measurement (figure 1).

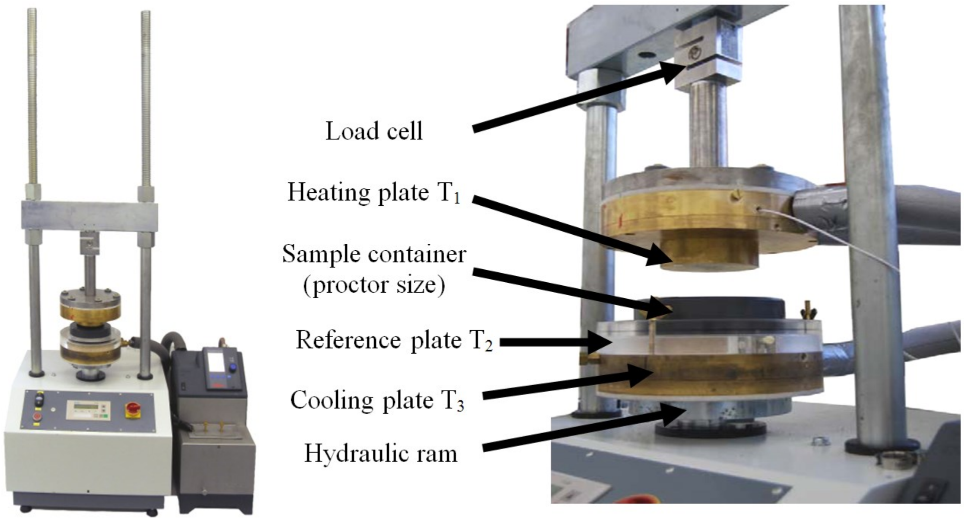

Figure 1: Thermal conductivity and diffusivity meter with a height of 1,80m (left), sample container and devices for measuring and regulating temperatures and preasures (right)

The thermal conductivity of the soil sample is determined with reference to plastic plates with known but different thermal conductivities and thermal diffusivities. The polymer plates were developed especially for the application in the device. Therefore the thermal conductivity of the plates can be adjusted to the expected thermal conductivity of soil samples. Within the plates, a miniature resistance temperature detector is positioned. The polymer plate is located on a steel cooling plate whose temperature is controlled with an accuracy of 0.05 °C. The sample is placed on the plastic reference plate. The temperature at the top of the sample is controlled by a heating plate. The measurement procedure is illustrated schematically in figure 2.

The temperature gradient within a homogeneous body (matrix and pore space filling) is linear. Thus the thermal conductivity of the sample can be calculated from the temperatures and distances and the known thermal conductivity of the reference plate. In contrast to a conventional divided bar apparatus (King, 1982) a temperature sensor is built-in directly into the reference plate. Contact resistances are reduced and the device is also able to measure thermal diffusivity.

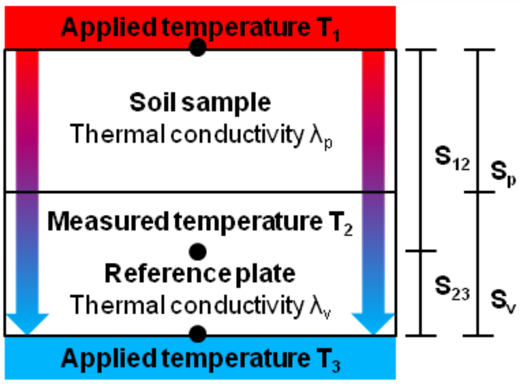

Figure 2: Measurement method. The temperatures T1 and T3 are regulated. T2 is measured. The thermal conductivity of the reference plate is known. The distances S (sample thickness and location of temperature sensors) are measured. The locations of the resistance temperature detectors are marked by black dots.

A basic constraint is that $T_1 > T_2 > T_3$ ensuring the heat flow occurs from top to bottom and that $T_1 > T_{ambient} > T_3$, so that heat flow from the environment does not penetrate to the center of the sample. Then equation 1 applies:

$$\frac{T_1 - T_3}{\frac{S_p}{\lambda_p} + \frac{S_v}{\lambda_v}} = \frac{T_2 - T_3}{\frac{S_{23}}{\lambda_v}} \tag{1}$$

where:

T_1	[K or °C]	Temperature of the heating plate
T_2	[K or °C]	Temperature of the reference
T_3	[K or °C]	Temperature of the cooling plate
λ_p	[$Wm^{-1}K^{-1}$]	Thermal conductivity of the sample
λ_v	[$Wm^{-1}K^{-1}$]	Thermal conductivity of the reference
S	[m]	Distances shown in figure 2

Thermal conductivity of the soil sample is calculated using, equation 2:

$$\lambda_p = \frac{\lambda_v \cdot S_p}{\left(\frac{T_1 - T_3}{T_2 - T_3}\right) \cdot S_{23} - S_v} \tag{2}$$

4. METHOD FOR COUPLED MEASUREMENT OF HYDRAULIC AND THERMAL PROPERTIES

The method of choice to determine the hydraulic properties of soil depends largely on the properties of the pore space, mainly its tortuosity, size and shape. The parameters of each experiment have to be adjusted to match the pore space, as well as the unconsolidated rock's behavior. Both are controlled by the matrix, which is mainly characterized by grain size, shape and surface characteristics as well as the degree of consolidation. Therefore the Geothermal Science and Technology work group at the TU Darmstadt is investigating methods to determine the hydraulic characteristics of partly saturated unconsolidated rocks with simultaneous testing of thermal conductivity and thermal diffusivity. The selection of the procedure (figure 3) also depends on the pressure-parameters to be determined. In a columnar test parameters for sands (capillary pressure 0 – 10,000 Pa) underdrained and wetted conditions are determined. By using a pressure-plate extractor unconsolidated rocks can be measured with capillary tensions up to 1 MPa. This tension is sufficient for the investigation of the soil water suction hysteresis of sand, silt and most clay fractions. An evaporation method can be applied to all types of soils. In contrast to the other methods it allows the measurement only underirrigated conditions. (Drefke et al., 2015)

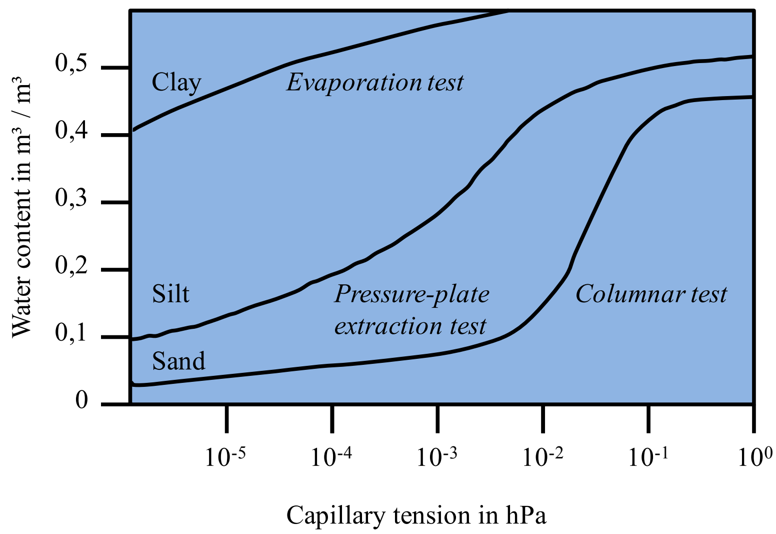

Figure 3: Types of unconsolidated rock and associated methods to measure their hydraulic properties.

The evaporation test after Schindler (1980 and 2010) is a simplification of the approach of Wind (1968). Two tensiometers are installed in a soil core sample at different depths. The tensiometers are located at equal distances from the center of the core sample (Figure 4).

Additionally to the design described by Schindler our system is equipped with a full-space line source after Blackwell, 1954 to determine the thermal conductivity. This allows the simultaneous measurement of thermal conductivity, water retention characteristics and hydraulic conductivity of a soil sample up to the entry point of air into the ceramic tensiometer (approx. 8,000 hPa). For doing a measurement the sample is fully saturated with water and placed on a balance. The surface of the cylinder is open to the atmosphere and the water can evaporate freely.

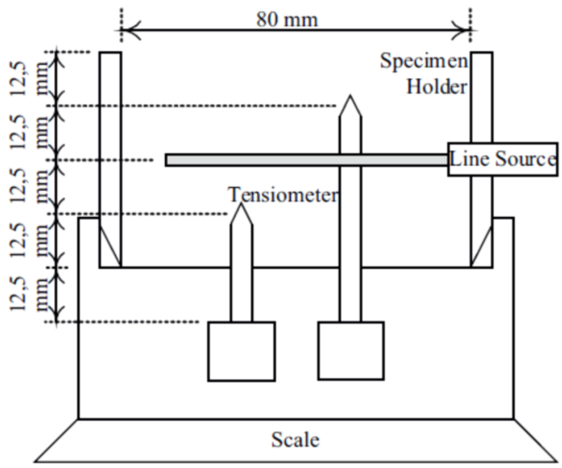

Figure 4: Evaporation test (Schindler, 1980) and line source (Blackwell, 1954) combined by Sass and Stegner (2012).

From the measured capillary tension and the hydraulic gradient the mean matrix potential is calculated. From the mass differences of the water the flow of water is calculated. After completion of the experiment the remaining water content is determined by drying the sample at 105°C and weighing the dried sample.

From these values the retention curve and unsaturated hydraulic conductivity are derived. In the course of an experiment, the evaporation potential increases rapidly with increasing desiccation of the specimen. By using a special tensiometer it is possible to measure the water potential up to the point of cavitation. At the onset point of cavitation the measured suction pressure abruptly decreases to the vapor pressure (about 1000 hPa). From this point on the measured values are no longer representative for the water pressure. Then a gas bubble forms just below the ceramic of the tensiometer and a small quantity of water moves from the tensiometer to the soil. This quantity of water is negligible when measuring the weight of the sample.

Capillary tension of the surrounding soil increases steadily until air enters the tensiometer and causes a complete draining of the larger pores within the ceramic tensiometer. The point of air intake is marked by a sudden decrease of the measured capillary tension to 0 hPa. From the point of the onset of cavitation to the point of air intake the capillary tensions are obtained by extrapolation (according to Schindler, 2010).

5. RESULTS

5.1 Geotechnical and soil physical properties

Three natural unconsolidated rocks: sand, silt and clay were tested to represent non-cohesive as well as cohesive soils. The grain size distribution curves of the soils are shown in figure 5. Further soil properties are illustrated in Table 3 and 4.

Table 3: Soil properties of the cohesive soils

Test soil type	Acronym according to DIN 18196	Grain density	Proctor density	Water content at Proctor density	Loss on ignition	Liquid limit	Plastic limit	Index of plasticity
	-	g/cm³	g/cm³	%	%	%	%	%
Clay	U, t, fs'	2,75	1,76	19,8	2,5	33.7	21.4	12.3
Silt	U, t', fs'	2,67	1,83	14,7	1,9	23.3	21.8	1.5

Table 4: Soil properties of the non-cohesive soil

Test soil type	Acronym according to DIN 18196	Grain density	Loosest packing	Densest packing	Porosity at loosest packing	Porosity at densest packing	Loss on ignition
	-	g/cm³	g/cm³	g/cm³	-	-	%
Sand	fS, ms*	2,66	1,23	1,65	0,54	0,38	1,1

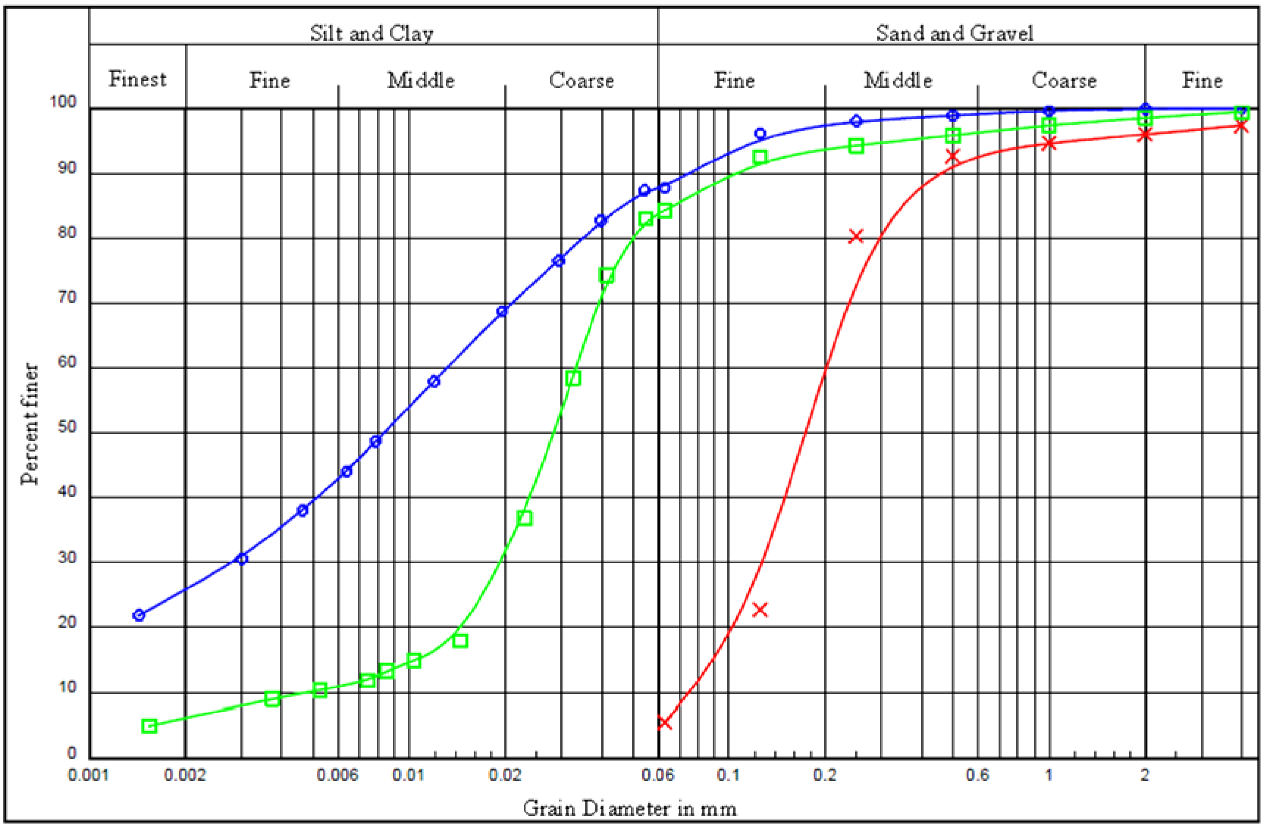

Figure 5: Grain-size distribution of the investigated soils. Nomenclature in brackets according to the European standard DIN EN ISO 14688-2. Blue: Clay (U, t, fs'). Green: Silt (U, t ', f'). Red: Sand (fs, ms *).

5.2 Geothermal properties

The measured values of thermal conductivity, capillary tension and water content are converted into continuous functions using curve fitting methods. The first function representing the capillary tension / thermal conductivity relationship (equation 3 and 4) was developed based on the Van Genuchten (1980) function. Figure 6 illustrates the resulting continuous function generated from measurements on a poorly sorted medium-grained sand.

$$\lambda(\psi) = \lambda_r + \frac{(\lambda_s - \lambda_r)}{\left[1 + (\alpha_\lambda \cdot |\psi|)^{n_\lambda}\right]^{m_\lambda}} \tag{3}$$

With:

$$m_\lambda = 1 - n_\lambda^{-1} \tag{4}$$

λ_r	[$Wm^{-1}K^{-1}$]	Drained thermal conductivity
λ_s	[$Wm^{-1}K^{-1}$]	Saturated thermal conductivity
α_λ	[m^{-1}]	Scaling parameter
n_λ	[-]	Inclination parameter

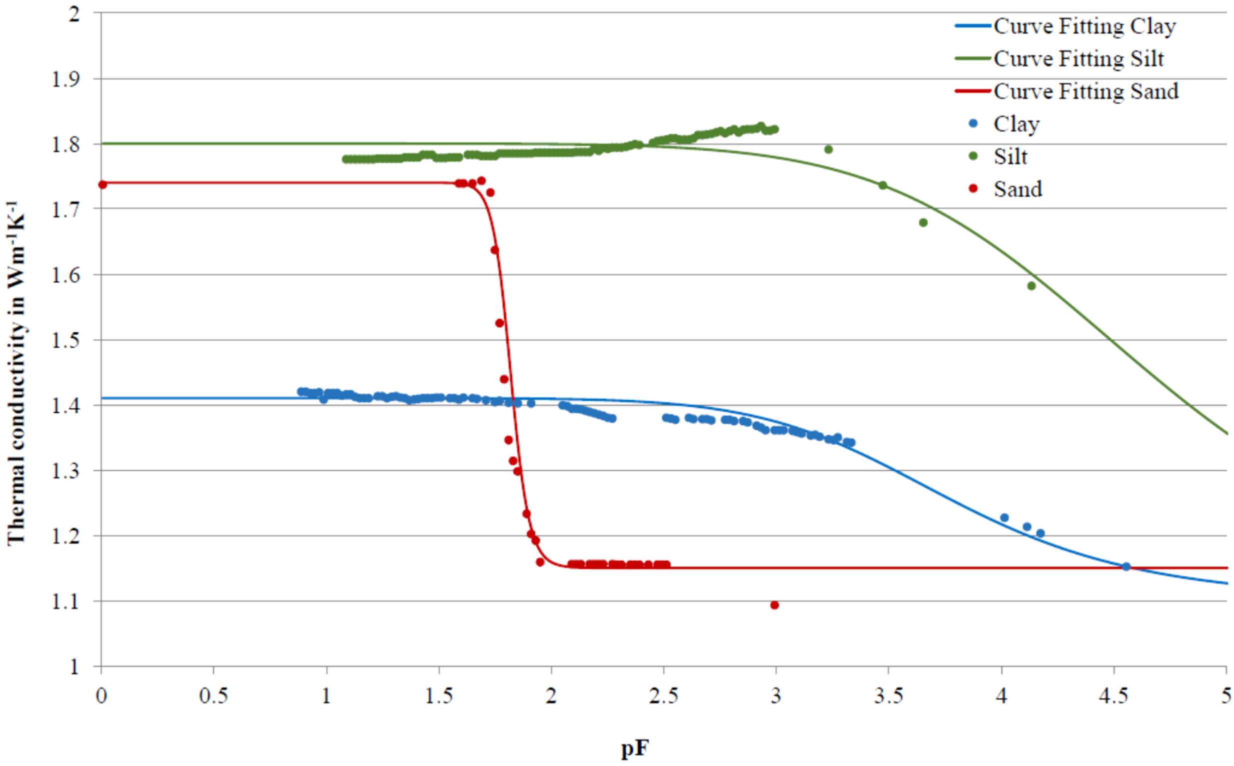

Figure 6: Measured and fitted capillary tension and thermal conductivity of different cohesive and non-cohesive soils.

SUMMARY AND OUTLOOK

The newly developed apparatus measures thermal conductivity and thermal diffusivity of unconsolidated rocks in a fully automated fashion. The measured variables are pressure and distance controlled at varying degrees of water saturation. This allows a reproduction of in-situ conditions regarding soil physical conditions and consolidation.

A series of experiments were conducted to investigate e.g. the relation between thermal conductivity, the capillary tension, water content and the unsaturated hydraulic conductivity. The tests were conducted under fully saturated, drained and irrigated conditions. The relation was then described by an equation and a fitting procedure was developed for the thermal conductivity as a function of capillary tension.

Important applications of the developed apparatus and methods are the dimensioning of geothermal plants and the determination of the thermal characteristics of the environment of onshore and offshore energy cables.

We thank for the financial support by the DFG in the framework of the Excellence Initiative, Darmstadt Graduate School of Excellence Energy Science and Engineering (GSC 1070).

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