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COUPLED MEASUREMENTS OF THERMOPYSICAL AND HYDRAULICAL PROPERTIES OF UNSATURATED AND UNCONSOLIDATED ROCKS

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ABSTRACT

Thermal conductivity and diffusivity as well as the hydraulic properties of unconsolidated rocks are the most important parameters required to quantify subsurface conductive and convective heat transfer. Soil mechanical and mineralogical constraints such as thermal conductivity of the individual grain fractions, the bulk dry density and the pressures remain constant. On the other hand, temperature and water content in the unsaturated zone are highly variable in time and space. The variations of the ratio between the gas phase and the water phase occupying the pore space has a varying thermal insulating effect due to the low thermal conductivity of air. In addition, the unsaturated hydraulic conductivity is a function of the water content of unconsolidated rocks. The air in the pore space reduces the effective conductive cross-sectional area, which leads to a decrease in hydraulic conductivity. Increasing drainage induces negative pore pressure (suction) and due to the hysteresis in drainage and irrigation thus the local water distribution is changed.

Presented herein is the implementation of a newly developed thermal conductivity and thermal diffusivity meter for the integrated investigation of soil mechanics, hydraulic and geothermal properties of unconsolidated rocks. Patent applications are pending. Furthermore an evaporation test was developed and columnar drainage experiments with continuously conducted measurement of water content, pore pressure, and thermal conductivity at different levels of the column. To simultaneously measure the hydraulic properties as well as the unsaturated thermal conductivity they are equipped with a full-space line (heat) source.

In these experiments many different unconsolidated rocks are examined in order to provide the respective parameters for a new capillary tension/ thermal conductivity function analogue to the existing capillary tension/ water content functions.

INTRODUCTION

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
Grainsize	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

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

However to determine the convective heat transport behavior additionally the unsaturated hydraulic conductivity and water retention function, largely depending on the tortuosity of the pore space, have to be determined simultaneously.

PRESSURE, TEMPERATURE AND VOLUME CONTROLLED MEASUREMENT

Apparatus and method

A newly developed thermal conductivity and diffusivity meter is employed for the integrated study of soil mechanics, hydraulic and geothermal properties of unconsolidated rocks (Stegner et al., 2011). The apparatus consists of a control panel, data acquisition, and data analysis software. It 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. Patent applications for the apparatus are pending.

The references are plastic plates with different thermal conductivities and thermal diffusivities. The thermal parameters of the plates are adjusted by ceramic fillers and precisely known. Therefor the thermal conductivity of the plates can be adjusted to the samples expected thermal conductivity. Within the plates an extremely thin PT 100 temperature sensor is placed. The plate is located on a 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 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 the divided bar apparatus described e. g. by King (1982) the temperature sensor is built-in directly into the reference plate. Contact resistances are reduced and the device is also able to measure thermal diffusivity.

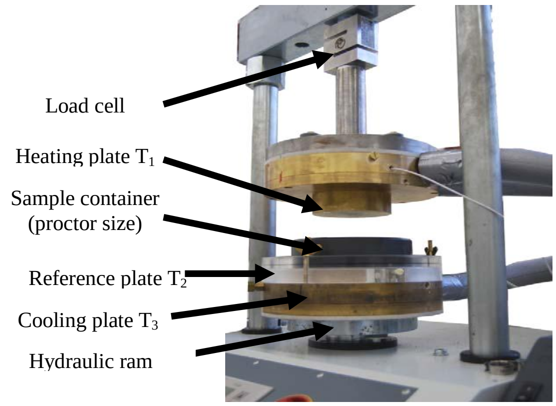

Figure 1: Thermal conductivity and diffusivity meter.

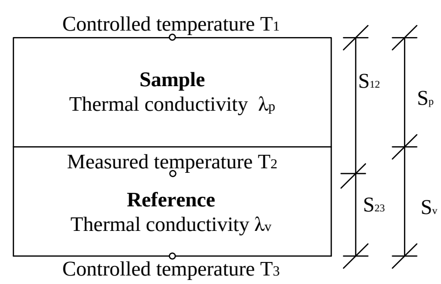

Figure 2: Measurement method. The temperatures T_1 and T_3 are regulated. T_2 is measured. The thermal conductivity of the reference plate is known. The distances S (sample thickness and location of temperature sensors) are measured.

Thermal conductivity

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 is:

T_1	[K or °C]	Temperature heating plate
T_2	[K or °C]	Temperature reference
T_3	[K or °C]	Temperature cooling plate
λ_p	[W/(Km)]	Thermal conductivity sample
λ_v	[W/(Km)]	Thermal conductivity reference
S	[m]	Distances shown in figure 2

It follows the thermal conductivity of the soil sample after equation 2:

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

Thermal diffusivity

Currently different ways for measurement and calculation of the thermal diffusivity are tested. One is bringing in a temperature impetus and measuring the time for passing through the sample. From this value the thermal diffusivity can be calculated. Here one measurement method using periodically temperature oscillation at the surface of the sample is described. The phase-delay Δt of the temperature oscillation in the reference plate is measured and is used with the known thermal diffusivity of the reference plate to calculate the thermal diffusivity of the sample. Figure 3 illustrates the process. The temperature T_1 at the samples upper surface is changed periodically. The temperature T_3 at the bottom of the reference plate is held constant and the temperature within the reference plate T_2 is measured. The amplitude ΔT_2 of the measured temperature oscillation is lower than the amplitude of the induced oscillation ΔT_1. The thermal diffusivity is calculated after Prinzen et al. (1990) and the thermal conductivity is derived from the values of the steady state phase after equation 2.

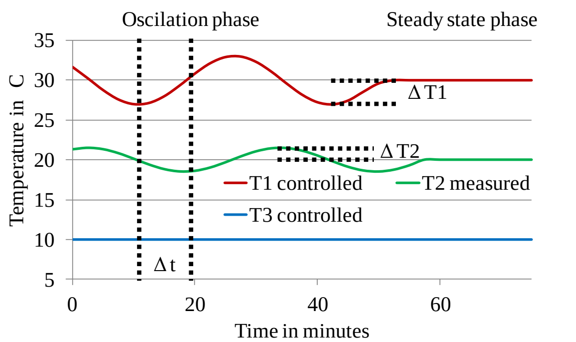

Figure 3: Example for the periodical temperature oscillation method to determine the thermal diffusivity.

Validation

The efficient operation of the apparatus was validated by calibration measurements and numerical calculations using the Abaqus finite element simulation software and unconsolidated rock standards. The geometry and the grid for the finiteelement model are shown in figure 4 and 5.

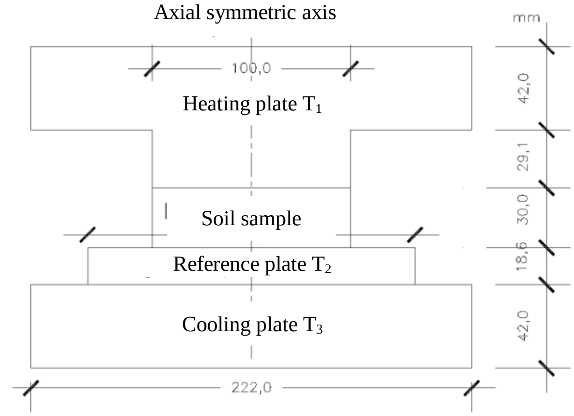

Figure 4: Geometry of the finite element modelling

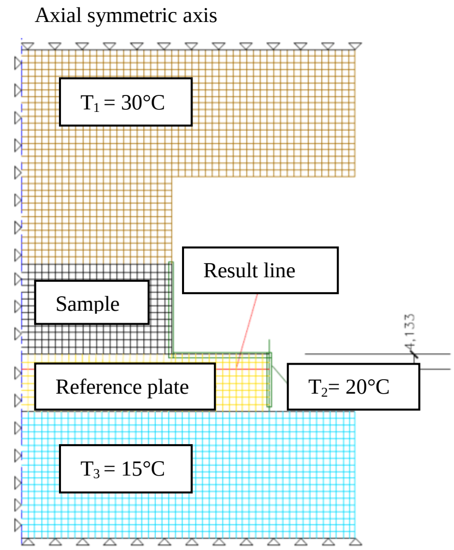

Figure 5: Grid of the finite element modelling.

The discrepancies between the modeled and measured values are approximately 0.1 %.
Moreover to test the practical handling and the accuracy of the device blind tests in two soil mechanical laboratories were carried out, additionally to the tests at the HydroThermikum of the TU Darmstadt. In these laboratories various volumes of unconsolidated reference rocks were tested by different laboratory operators. The staff was not specially trained for geothermal parameter testing. The results are shown in figure 6.

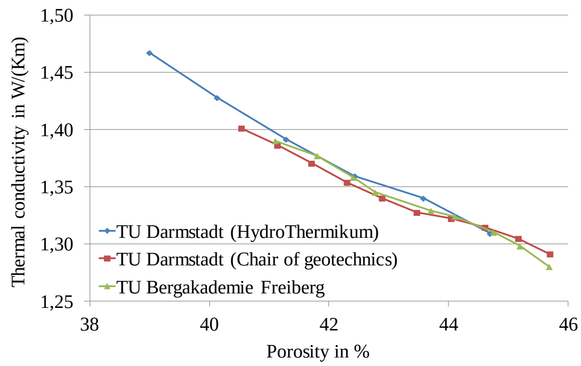

Figure 6: Blind test results performed by two different laboratories on different volumes of weathered granodiorite detritus in comparison with results attained at the TU Darmstadt Lab HydroThermikum.

The reproducibility of the measurements carried out in all three laboratories was greater than 97 %. It can be concluded that the newly developed method and device for the measurement of thermal properties of unconsolidated and unsaturated soils was proven to be adequate to solve the investigation problems.

COUPLED MEASUREMENT OF HYDRAULIC AND THERMAL PROPERTIES

Methods

The method of choice to determine the hydraulic properties 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. The Chair of Geothermal Science and Technology therefore is investigating methods to determine the hydraulic characteristics of partially saturated unconsolidated rocks combined with simultaneous measurement of thermal conductivity and thermal diffusivity. Three main experimental procedures applied to determine the capillary tension, the saturation (water content) and the partially saturated hydraulic conductivity provide the basis. These procedures are adjusted to additionally allow the simultaneous measurement of the thermal conductivity and thermal diffusivity. The choice of the procedure also depends on the parameters to be determined. In a columnar test parameters for sands (capillary pressure 0 – 10,000 Pa) under drained and irrigated 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 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 under irrigated conditions.
The evaporation test and the columnar test are described in the following chapters.

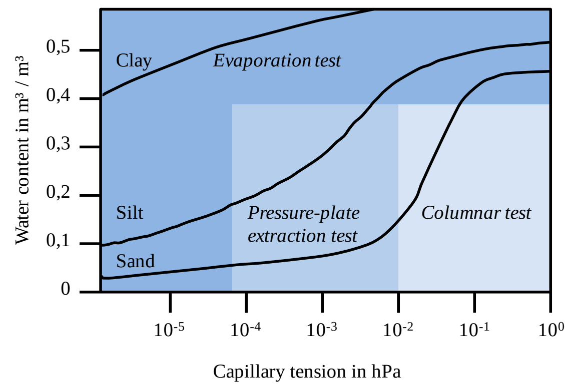

Figure 7: Types of unconsolidated rock and associated method to measure their hydraulic properties.

<u>Evaporation test</u>

The evaporation test after Schindler (1980) 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 8).

Figure 8: Evaporation test after Schindler (1980). Open device with tensiometer (left) and with fitted soil sample (right).

Additionally to the design described by Schindler it is equipped with a full-space line source (after Blackwell, 1954) to determine the thermal conductivity. This allows the simultaneous detection 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 towards the atmosphere and the water can evaporate freely.

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 (figure 9). 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.

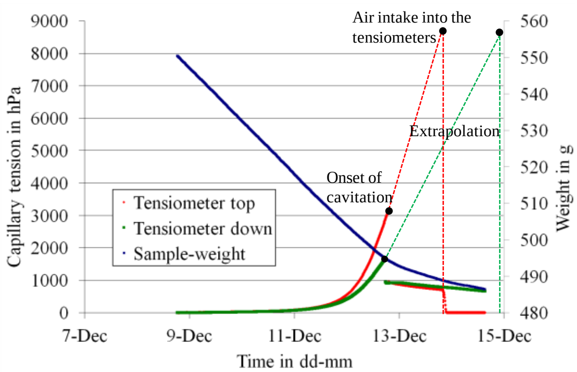

Figure 9: Tension and weight of weathered ganodiorite detritus during an evaporation test.

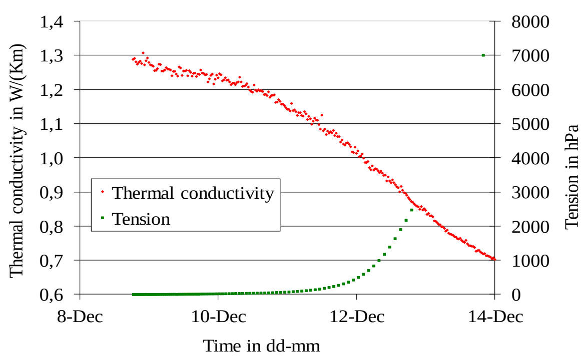

Figure 10: Thermal conductivity and tension of weathered ganodiorite detritus during an evaporation test.

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).

Calculation of the hydraulic conductivity

The calculation of the conductivity function is based on the Darcy equation, assuming that the water tension and water content are linearly distributed over the column height and assuming that the change of water tension and the change of sample weight between two measured points in time (usually 5 sec. interval) is linear. The unsaturated hydraulic conductivity may be calculated as shown in equation 3.

$$K(h) = \frac{\Delta m}{2A \cdot \Delta t \cdot i_m \cdot \rho_W} \qquad (3)$$

With:

$$i_m = \frac{1}{2} \cdot \left(\frac{\Psi_{t1,up} - \Psi_{t1,down}}{\Delta z} + \frac{\Psi_{t2,up} - \Psi_{t2,down}}{\Delta z} \right) \qquad (4)$$

Where is:

K(h)	[m/s]	Unsaturated hydraulic conductivity
ρ	[kg/m³]	Density
m	[kg]	Mass of water
A	[m²]	Area of the sample
i_m	[-]	Average hydraulic gradient
Ψ	[m]	Capillary tension
Δz	[m]	Distance between tensiometers

Columnar Test

The columnar test apparatus (figure 11) has a height of one meter and an inner diameter of 22 cm. Stratifications of different soils and measurement devices or probes may be installed at different levels. At the beginning of the experiment the soil is saturated. Then the water is gradually drained. After reaching the respective equilibrium state the capillary tension is measured by means of tensiometers and the associated volumetric water content by frequency-domain-reflectometry (FDR) sensors (figure 12). The measurement of thermal conductivity is carried out in the same way as in the evaporation experiment by using half-space and full-space probes according to the line source theory. In figure 11 the typical measurement equipment is shown. To obtain precise measurement results the FDR-sensors must be calibrated for the specific soil after Starr &

Paltineanu (2002). The FDR moisture measurement technique relies on measuring the electrical capacitance of the soil. The capacitance depends on the quantitative composition of the soil - air – water system.

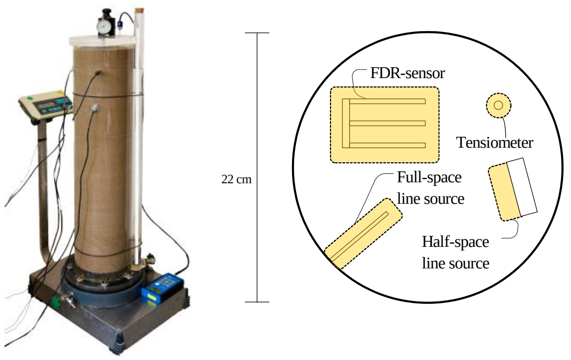

Figure 11: Columnar test (left). Typical arrangement of probes at one level within the column (right): line source devices for measuring the thermal conductivity, tensiometer for measuring capillary tension and FDR-sensor for the measurement of water saturation. The corresponding measuring range is colored yellow.

The dimensionless dielectric constant of water is about 80 of dry soil particles it is less than 8. The exact values of the dielectric constants are stated in figure 13. Due to the differences of the dielectric constant between grains and water, the water content can be calculated from the measured capacitance.

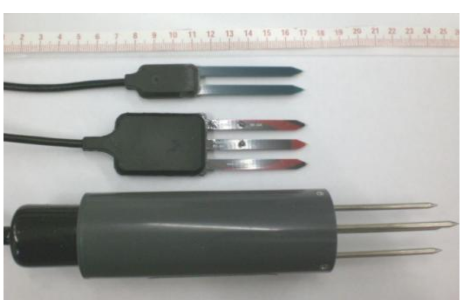

Figure 12: Different types of frequenzy domain reflectometry sensors which are used in the columnar test.

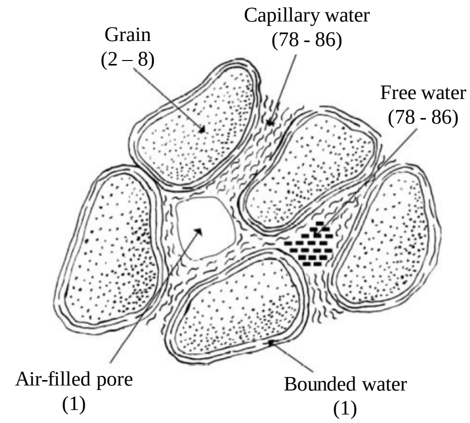

Figure 13: Dielectric constants of soil components (after Scheuermann et al., 2002).

The intensity of the influence of the inhomogeneities of the sample on the measured value, according to Cepuder & Hauer (2003), decreases with the square of the distance. Thus careful sample preparation in the direct surrounding of the probe is necessary. The readout of the measured data is done pointwise by a handheld or constantly by data loggers. This experiment allows the measurement of soil samples under realistic conditions. From the measured values capillary tension/ water content, water content/ thermal conductivity or capillary tension/ thermal conductivity curves can be plotted. The curve fitting is conducted in the same way as described for the evaporation tests.

Calculation of the relationship of saturation, water potential and thermal properties

The measured values are transformed into continuous functions by using several curve fitting procedures (e.g. Durner & Or (2005), Brooks & Corey (1964) and van Genuchten (1980)). The method of curve fitting is applied to transform the measurements to a continuous water content/ capillary tension curve. It is tested, which curve fitting procedure provides the best fit between measured values and the adjusted curves. Equation 5 shows the curve fitting method for hydraulic parameters after van Genuchten. An analogue fitting method has been developed for the thermal parameters (equation 7).

$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha \cdot |\psi|)^n\right]^m} \tag{5}$$

With:

$$\mathrm{m} = 1 - \frac{1}{\mathrm{n}} \tag{6}$$

Where is:

θ_r	[m³/m³]	Drained water content
θ_s	[m³/m³]	Saturated water content
α	[1/m]	Scaling parameter
n	[-]	Inclination parameter

$$\lambda(\psi) = \lambda_r + \frac{(\lambda_s - \lambda_r)}{\left[1 + (\alpha_\lambda \cdot |\psi|)^{n_\lambda}\right]^{m_\lambda}} \tag{7}$$

With:

$$m_\lambda = 1 - \frac{1}{n_\lambda} \tag{8}$$

Where is:

λ_r	[m³/m³]	Drained thermal conductivity
λ_s	[m³/m³]	Saturated thermal conductivity
α_λ	[1/m]	Scaling parameter
n_λ	[-]	Inclination parameter

The application of the equations is illustrated in figure 14 to 16 for a measurement series on a poorly sorted medium-grained sand with a grain density of ρ_s=2.68 g/cm³ and a porosity of n=0.43. The curve of the thermal conductivity as a function of water content increases continuously, though not linearly. The measured values of the capillary tension and saturation curve (figure 15) are transformed applying van Genuchtens method (equation 5). The fitting parameters α and n are adjusted, until the best fit is reached. The transformation results in a very good compliance. The similarly structured equation 7 is applied on the thermal conductivity and capillary tension curves (figure 16). Here too very good compliance is achieved. This method will be applied to a wide range of soils and unconsolidated rocks in order to establish a comprehensive database for the fitting parameters α and n of soil types for the capillary tension/ thermal conductivity curves. Thereby such curves may provide design values for the thermal conductivity of unconsolidated rocks.

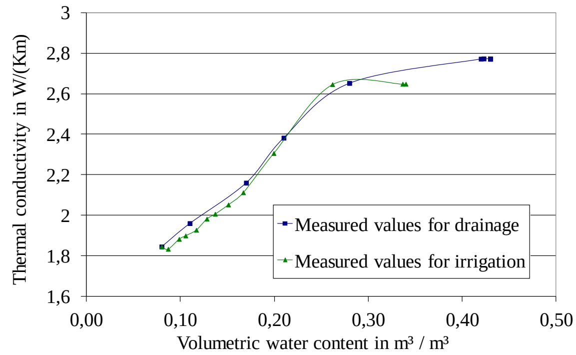

Figure 14: Water content and thermal conductivity of a poorly sorted medium-grained sand obtained by a columnar test.

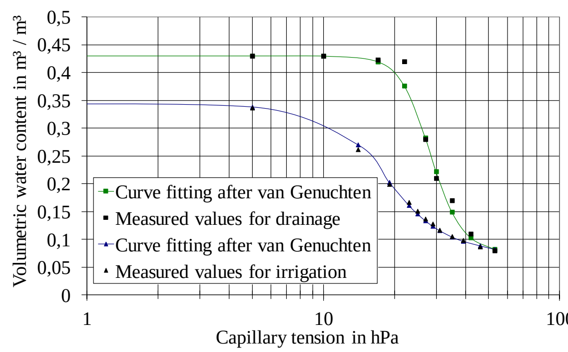

Figure 15: Capillary tension and water content of a poorly sorted medium-grained sand obtained by a columnar test.

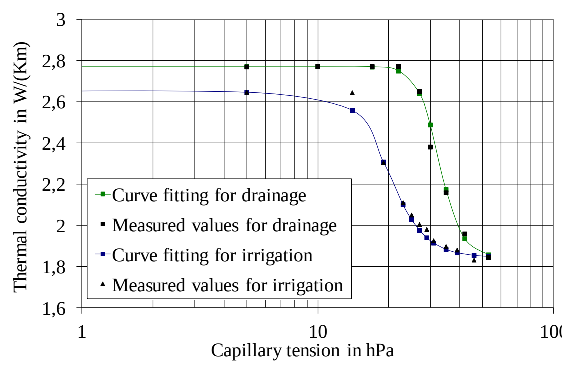

Figure 16: Capillary tension and thermal conductivity of a poorly sorted medium-grained sand obtained by a columnar test.

SUMMARY AND OUTLOOK

The newly developed apparatus measures thermal conductivity and thermal diffusivity of unconsolidated rocks fully automated. The measurement is pressure and distance controlled at varying degrees of water saturation. This allows a reproduction of in-situ conditions regarding soil physical conditions and consolidation. The measuring procedure was validated in numerical simulations and through blind tests and was applied in several investigations.

A series of columnar and evaporation experiments were conducted to investigate the relation between thermal conductivity, the capillary tension, water content and the unsaturated hydraulic conductivity. The tests were conducted under drained and irrigated conditions. The relation was there upon described in an equation and a fitting procedure was developed for the thermal conductivity as a function of capillary tension.

At present many different unconsolidated rocks are examined in order to provide the respective parameters for the capillary tension/ thermal conductivity function analogue to the existing capillary tension/ water content functions. All results will be validated against high resolution field experiments employing heated copper - fiber optic cables in boreholes at the TU Darmstadt testing grounds.

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