

Influence of the Hydraulic Properties of Unconsolidated Rocks and Backfill Materials on the Change of the Thermophysical Characteristics by Heat Transfer

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ABSTRACT

Due to varying thermal conditions in the ground caused by heat transfer or climate induced variations the local water content changes and consequently hydraulic and thermal properties change as well.

Besides the climate the exchange of heat in the partially saturated subsoil strongly influences its hydraulic and thermal properties.

It is important to be able to make reliable forecasts of the thermal and hydraulic properties of partially saturated soils and embedding materials for the design of structures and constructions using thermal energy in the shallow ground. The liquid water contained in partially saturated porous media is in direct interaction with the vapor phase of water. In particular, in addition to the conductive portion of the heat transported, the heat transfer in the vapor and the aqueous phase and the occurrence of a phase transition is of critical importance.

Resilient data of the hydraulic and thermal properties as a function of the water content are required for the simulation of changes in working conditions.

An evaporation test was accordingly developed which enables the simultaneous determination of several hydraulic and thermal parameters at variable water contents of soils and artificial bedding materials. From the data, an interrelation between thermal conductivity and water content, as well as an interrelation between thermal conductivity and water retention characteristics are derived. The retention characteristics of a backfill material or soil sample are determined in an evaporation test, while unsaturated hydraulic conductivity and thermal conductivity are measured simultaneously as a function of the water content. Thermal conductivity is determined using a full space line source embedded in the sample.

These tests are currently a variety of experiments carried out to generate a statistically representative number of measurements on different soil types and artificial bedding materials.

To provide technically and economically efficient heat input or heat withdrawal (e.g. through a seasonal heat storage installation), modelling of hydraulic and thermal properties of the backfill material and soil requires the input of reliable thermal and hydraulic parameters.

To implement these data into FEM modelling, it is necessary to describe them by mathematical expressions representing the interdependence of water retention, unsaturated hydraulic and thermal conductivity. Currently, various mathematical models are developed on the basis of these data and validated against the growing data set.

1. INTRODUCTION

In the course of the growing decentralized utilization of geothermal energy, many shallow geothermal installations will be constructed, in particular in footings and paved surfaces. The increasing expansion of regenerative energy sources requires the upgrading of supply networks.

Most of these installations are located on and in partially saturated soils, which due to the presence of water and air in variable proportions, form such a three-phase system. The changes of these properties in such porous three-component systems are much more difficult to predict than in pure porous two-component systems, such as solid and water or solid and air, because the additional third substance interacts with the two others.

It is of crucial importance for the efficiency of geothermal installations as well as for buried energy cables to have a good thermal conductivity of the geothermal system. For energy cables, for example, a high thermal conductivity is of immense importance to dissipate the waste heat safely, which occurs due to transmission. Not to damage electric insulation materials that surround the metallic conductor, temperatures above 70 ... 90°C must be avoided. Although below these temperature the transport capacity of the cables is temperature depending Cold cables can conduct more power. Thus, the heat dissipation of a soil has an important influence on the amount of energy which can be transferred by such a cable, and thus an economic impact on the construction of new cable trays.

In moderate latitudes, the extreme conditions of slack water or the complete drying of soils are encountered very rarely, however, those cases are currently considered as a priority for the planning and dimensioning of geothermal heat exchange by engineers. The uncertainties that arise from planning and dimensioning such installations while regarding the soil as a pure two-component-system, often lead to over- or under-dimensioning, misjudgment in economic analysis or in the worst case to technical failure.

In general, the properties of partially saturated, unconsolidated rocks are in a wide range between these two pure two component considerations (wet or dry conditions).

The changes of the physical properties in such three-component systems are much more difficult to predict than in pure two-component systems, such as soil-water or soil-air, because the additional third substance interacts with the two others.

As water has a much higher thermal conductivity than air, dewatering leads to retreating water menisci between soil grains. This results in a reduction of the thermal conductive cross-section. At the same time, the increasing air proportion in the pore space decreases the hydraulically conductive cross-section. In addition to a decrease in the transported heat due to convective water flow, this leads to an increased transport of water vapor.

In contrast to the heat capacity of unconsolidated rocks, which can be calculated from the heat capacity of their single components and volume fractions, thermal conductivity is not a linear function of the water content. Standards and regulations only represent approximate values for the thermal properties of soil types in saturated or dry conditions.

The thermal influence of geothermal installations and structures in these soils leads to changes in the water content and consequently altered hydraulic and thermal properties. When dimensioning of shallow geothermal installations or energy cable networks, reliable predictions of the geothermal properties of partially saturated soils and bedding materials are of critical importance. To provide a technically and economically efficient heat input (e. g. by short-term load peaks in the energy grid from renewable energy) or heat withdrawal (e. g. through a seasonal heat storage installation), modelling of hydraulic and thermal properties of the soil requires the input of reliable thermal and hydraulic parameters.

An evaporation test was developed, which allows for simultaneous determination of several hydraulic and thermal parameters during dewatering. The water retention characteristics of soil samples and backfill material-samples can be determined in this experiment, while the unsaturated hydraulic conductivity and thermal conductivity as a function of the water content are simultaneously measured. Thermal conductivity is determined using a full space line source embedded in the sample. From the data, the interrelation between thermal conductivity and water content as well as the interrelation between thermal conductivity and the water retention characteristics are derived. By this experiment it is possible to characterize undisturbed samples during dewatering in a wide range of capillary tensions.

Suitable adaptation functions convert the obtained data into mathematical expressions representing the interdependence of water retention, unsaturated hydraulic conductivity and thermal conductivity. They are implemented in FEM modelling of the thermal and hydraulic processes in the vicinity of underground cables and geothermal installations.

Backfill materials can be adapted individually to the respective requirements. By using backfill materials, which usually are in direct thermal and hydraulic contact with the surrounding soil, a drastic increase in heat exchange efficiency can often be achieved.

Thermal interference in these backfill materials and soils leads to changes in the water content and, consequently, to altered hydraulic and thermal properties. An improvement in the thermal conductivity is generally achieved by adding thermally conductive additives. These building materials reach higher thermal conductivities in wet and dry areas towards natural soils. Since the thermal conductivity of soil or building materials depends on their water content, hydraulic optimization of the bedding material can be an enormous benefit for its thermal properties.

Thus, an improved water retention capacity of artificial bedding materials can achieve a preservation of moisture content and therefore good thermal conductivity in the area around heat exchangers, even without the use of expensive, thermally conductive additives.

2. MATERIALS AND METHODS

An evaporation test experiment was developed by continuously measuring the water content, pore pressure, and thermal conductivity at different levels of a soil sample or artificial bedding material column. These measurement techniques allow for simultaneous measurement of the hydraulic properties as well as of unsaturated thermal conductivity by using a full-space line (heat) source. In this experiment, undisturbed soil samples and hydrated backfill materials are characterized during dewatering. Currently many different unconsolidated rocks are examined in these experiments in order to provide the respective parameters for the development of thermal conductivity/saturation and thermal conductivity/capillary tension functions analogous to the existing capillary tension/ water content functions. In addition, this experimental set-up will be used to develop new thermal and hydraulically optimized bedding materials. All results will be validated against high resolution field experiments.

2.1 Evaporation Test

An evaporation test according to Schindler (1980), a simplification of the approach by Wind (1968) allows for simultaneous detection of the water retention characteristics and the unsaturated hydraulic conductivity of a soil sample in a very wide range of relevant capillary tension measurements. By adding a full-space line source according to Blackwell (1954), thermal conductivity can be determined simultaneously during this test. This experimental setup allows for determination of relationships between thermal conductivity and capillary tension or thermal conductivity and water content in conditions of desorption. By using the method according to Schindler (2010), it is possible to determine these parameters from saturation up to capillary tensions far above 4000 hPa (usually up to 6000-8000 hPa).

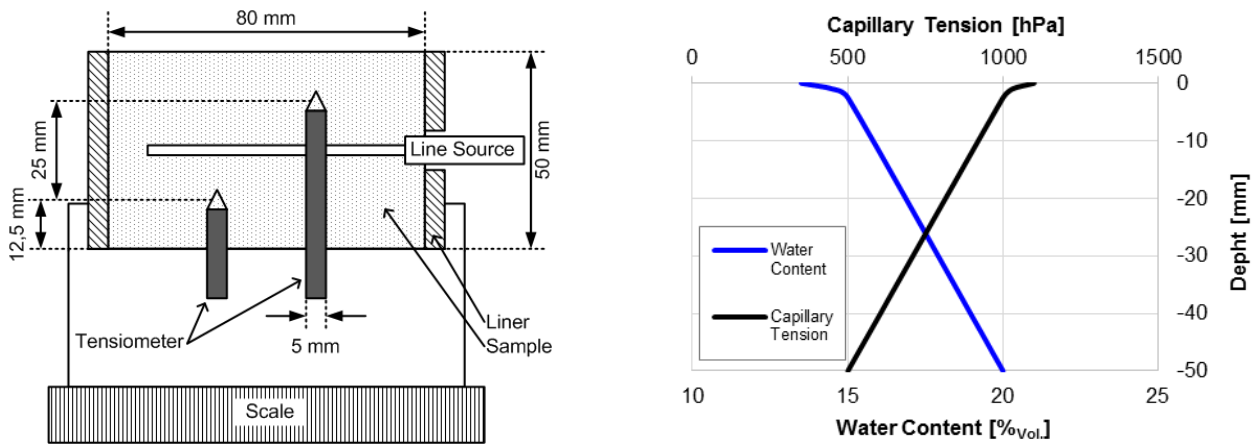


Figure 1: Sectional view across the evaporation test device (left); Sketch of the assumed linear gradients of water content and matrix potential in the depth of the tensiometer measurements (right).

For measuring purposes, the core sample initially has to be fully saturated with water and closed on the bottom. Then the whole measuring device has to be placed on a balance (Fig. 1, left). The surface of the cylindrical sample is open towards the atmosphere so the water can evaporate freely. During evaporation, the weight of the entire assembly and the corresponding capillary tension are recorded over time. The absolute water content of each single measuring process is calculated at the end of a test by determining the residual water content and the weight loss during the measuring process. From the measured capillary tension and the hydraulic gradient, the mean matrix potential and unsaturated hydraulic conductivity for the plane between the two tensiometers are calculated.

From the mass differences of the water, the water flow is calculated. From these values, thermal conductivity, capillary tension as well as unsaturated hydraulic conductivity in dependence of the water content are derived.

While increasing dehydration of the sample by evaporation, the capillary tension increases progressively (figure 2). By using special tensiometers in this experiment, it is possible to measure the capillary tension up to a point well above the boiling point of free water (Schindler, 2008). With increasing capillary tension, cavitation occurs. The measured tension drops abruptly towards the vapor pressure of water (about 1000 hPa). From this point on, the measured values are no longer directly representative for the surrounding soil water pressure.

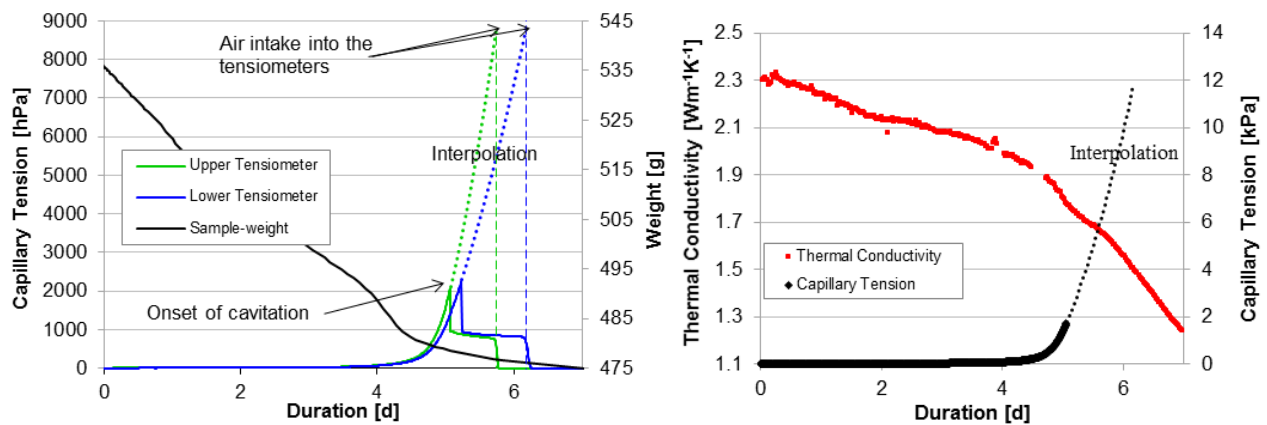


Figure 2: Tension and weight of a sand sample during an evaporation test (left; modified after: Schindler, 2010); Thermal conductivity and capillary tension of a sand sample during an evaporation test (right; modified after: Sass and Stegner, 2012)

If the capillary tension of the sample increases up to the known air entry point of the tensiometer ceramic, the measured soil water pressure drops down to zero. At this point, the water content is regarded as an additional point for the air entry pressure of the ceramic cup of the tensiometer. Between the onset of cavitation and the point of air intake, capillary tensions are obtained by extrapolation (according to Schindler, 2010).

While assuming a linear gradient of the capillary tension (Fig. 2; right), the average capillary tension Ψ_m at the height of the thermal conductivity measurement is calculated according to equation 1.

$$\Psi_m = \frac{1}{4} \cdot (\Psi_{t1,upper} + \Psi_{t1,lower} + \Psi_{t2,upper} + \Psi_{t2,lower}) \quad (1)$$

Ψ_m : average capillary tension

$\Psi_{t,i,y}$: capillary tension at time point t at the upper and lower tensiometer

With increasing evaporation of water from the sample, thermal conductivity decreases, while the tension at the location of thermal conductivity measurement rises increasingly (Figure 2; right).

2.2 Validation of the results in a large field test

To validate the results of laboratory tests in natural conditions, a test field was built to study the soil alterations when exchanging heat with different unsaturated soils. The test field is used to investigate temperature distribution and water movements related to different operating scenarios of underground cables in natural climatic conditions. Underground cables emit considerable amounts of heat while transferring electric current, which must be dissipated from the soil. In order to ensure reliable operation of these cables, the conductor temperatures should not exceed a maximum of 90 ° C. Since the temperature rise is related directly to the amount of the current within a conductor, an exact calculation of the maximum attainable temperature of the cable depending on the soil and its daily load curve is of enormous economic interest. This thermal stress within the surrounding soil can lead to its drying, this often results in a drastic reduction in the fortune of the heat dissipation.

The overall dimension of the buried cable test field is 14 m by 6 m, divided into four sections of 3.5 m length. Various cable configurations of middle and low voltage cables (0.4 to 20 kV) according to the German standard DIN will be embedded in the field at a depth of 0.75 m (across the entire field) (Figure 3).

The individual sections are hydraulically independent, as they are segregated by an impermeable plastic layer. In fields “clay” and “silt”, the naturally occurring sand on site will be replaced by well-defined clay and silt down to a depth of 2.5 m. In field “sand”, the naturally occurring sand will remain and field “thermal improved material” will contain thermally enhanced bedding material, currently being developed in co-operation with a cement manufacturer (HeidelbergCement AG).

View of the test field

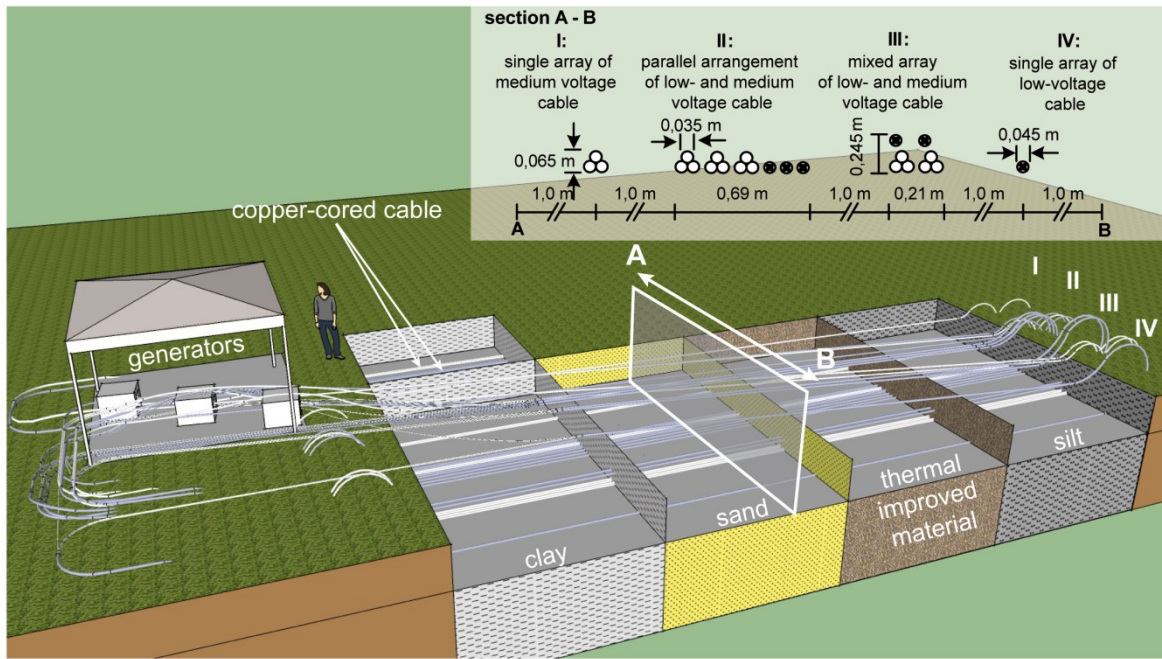


Figure 3: Test field for buried cables. The position and arrangement of several cables are designed according to the German standards (Stegner et al., 2015)

The variations of the thermal and hydraulic conditions in the test field are monitored by several types of sensors. 16 tensiometers measure the capillary pressure; 16 FDR sensors measure the water content and more than 80 Pt100 resistance temperature detector measure the temperature of the metallic conductors, the cable surface and the surrounding soil. In addition, thermal variations inside the fields are recorded by optic fiber cables applying the Distributed-Temperature-Sensing (DTS) method and are laid out and buried in loops. The data will be correlated with weather data, i.e. temperature, precipitation and solar radiation, and validated in coupled thermal-hydraulic numerical models.

3. RESULTS AND CONCLUSION

3.1 Evaporation Test

To implement thermally induced water movement and the related interactions with variable thermal characteristics of a soil into simulation models it is necessary to have precise mathematical characterization of these properties. A diagram of measurement

results of the thermal conductivity of different sand samples over their saturation clearly illustrates the soil type depending differences (Fig. 4 left). In the standard VDI 4640 Part 1, the thermal conductivity of dry sand is indicated by a value of 0.3 to 0.8 $\text{Wm}^{-1}\text{K}^{-1}$, the one of saturated sand by 1.7 to 5 $\text{Wm}^{-1}\text{K}^{-1}$.

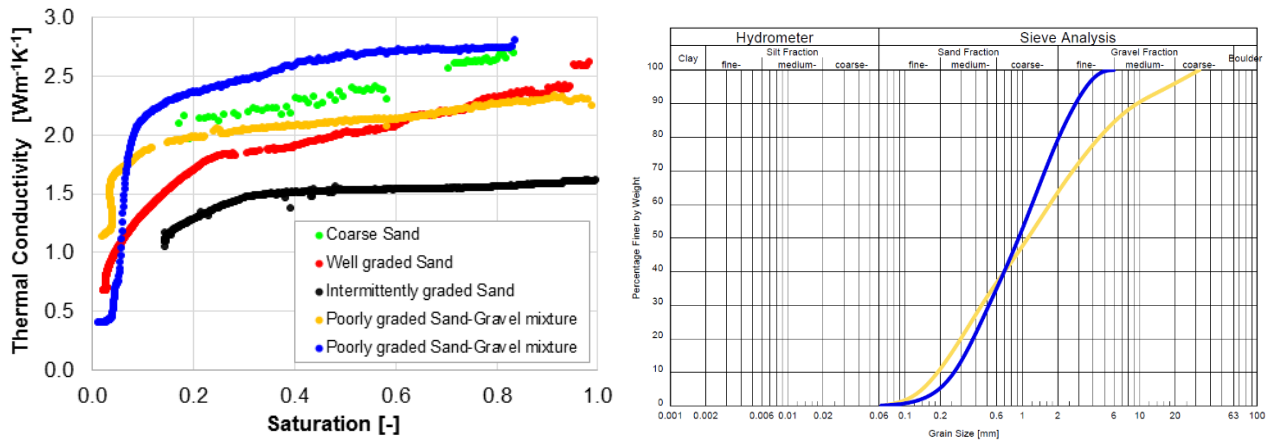


Figure 4: Laboratory investigation of the thermal conductivity of sand samples as a function of saturation (left; modified after: Stegner et al., 2013); Grain particle distribution of the investigated sand samples (right).

Sands featuring a main content of particle sizes of one small range, are described as poorly-graded, whereas well-graded sands are homogeneous mixtures containing diverse particle sizes. Intermittently-graded sands feature several pre-dominant particle sizes.

Figure 4 left shows that based on a predominant grain size, only an inaccurate estimation of the thermal conductivity can be made considering a certain water content. The course of the thermal conductivity between the saturated and the dry condition largely depends on the properties of the pore space, mainly its tortuosity, size and shape. These parameters are controlled by the matrix, which is mainly characterized by grain size, shape and surface characteristics, mineralogy as well as the degree of consolidation.

The distribution of the soil water in defined pore spaces at different water contents is represented by the capillary tension/water content relationship. In Figure 5 on the left, this relationship between the water content of capillary tension and the drainage of the sands of Figure 4 is shown. From this proportionality, a statement on the pore size distribution can be made.

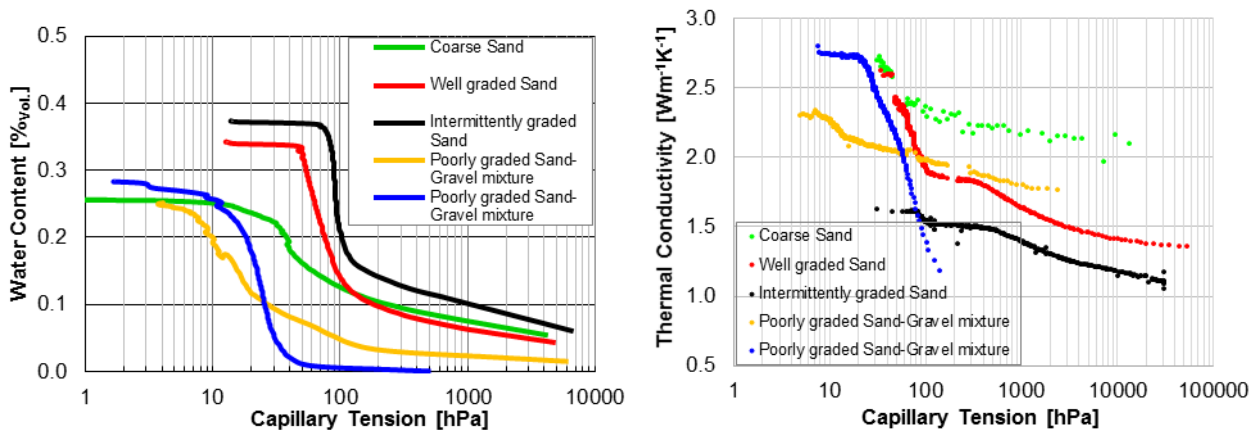


Figure 5: Water content of sand samples as a function of capillary tension (left); Thermal conductivity of sand samples as a function of capillary tension (right) (Drefke et al., 2013).

A temperature change is accompanied by a change in the water vapor pressure, this leads to an alternating heat load of heat exchangers inside the unsaturated zone caused by evaporation or condensation processes. Since all water motions are driven by potential gradients, it is necessary to investigate the hydraulic and thermophysical properties in regard to the hydraulic potential.

For example, the pore space of coarse grained soil (Figure 5, blue) is dominated by large pores which can be drained even at low capillary tensions.

Since this soil is sensitive to changes in the water content, drainage of these pores leads to a drastic decrease in thermal conductivity. As shown in Figure 5 on the right, other soils show significantly less changes in thermal conductivity, despite a considerable decrease of the water content in ranges up to capillary tension of 200hPa.

The soils (Figure 5, yellow and blue) which are described as being identical according to the German standard DIN 18196, reveal completely different characteristics of thermal conductivity with increasing capillary tension.

With increasing dewatering of the soil, coarse pores are dewatered first and subsequently the finer and finer pores.

Water, which, in the form of menisci, is located between the grains of soil, can be removed only at high capillary tension. If, with sufficiently high capillary tension, these menisci run dry, thermal conductivity will decrease drastically.

3.2 Optimization of artificial bedding materials

The use of thermally enhanced beddings is common in shallow geothermal energy systems, for example when backfilling borehole heat exchangers. To improve the thermal properties of artificial bedding materials, one development approach of recipes uses the addition of heat conductive additives, another development approach combines the mineral fillers of a recipe in a way to achieve high dry density of the hardened material.

In Figure 6 you can see two different backfill materials without thermal conductive additives in light grey and light blue. This Figure also shows two thermally enhanced materials (by adding thermal conductive additives to the grout) in dark grey and dark blue, based on the original material. The data in the range of moisture content were determined in the evaporation experiment described in Section 2. Thermal conductivity in the dry state was measured using the thermal conductivity scanning method of samples of corresponding material ($n > 3$).

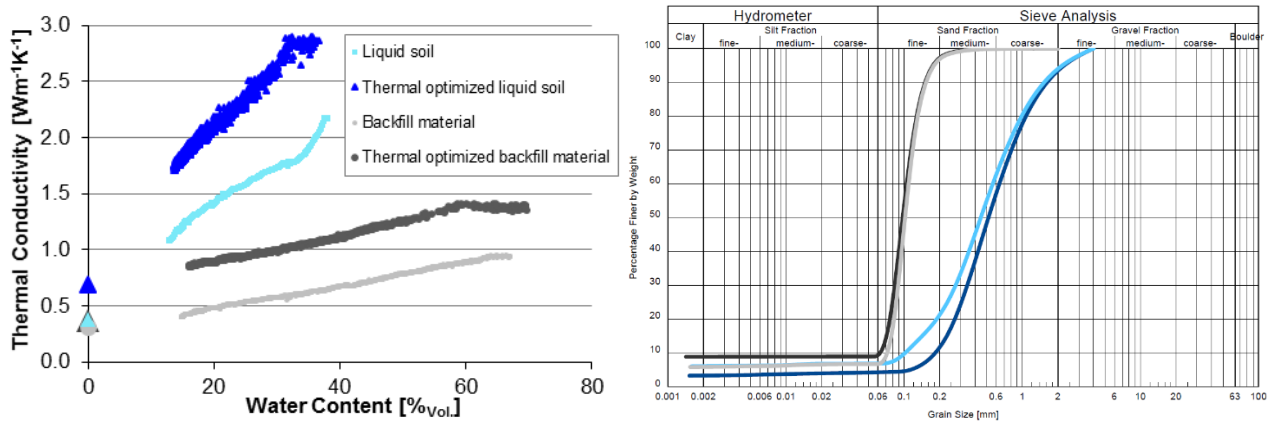


Figure 6: left: Thermal optimization of artificial embedding materials by using thermal conductive additives (left); Grain size distributions of the dry components before hydration, without cement and plasticizer (right).

Figure 6 reveals an improvement in thermal conductivity of approximately about $0.5 \text{ Wm}^{-1}\text{K}^{-1}$ which was achieved in both materials in the wet state by adding highly heat-conductive additives. In the dry state, however, a moderate improvement in thermal conductivity only shows in the coarse-grained liquid soil. The coarse-grained liquid soil predominantly consists of well-rounded quartz sand. The fine-grained backfill material predominantly consists of limestone marl meal. The particle size distribution of the poorly-graded sand with gravel (Figure 4 right, blue) and the initial material of the liquid soil (Figure 6, right light blue) have a very similar shape.

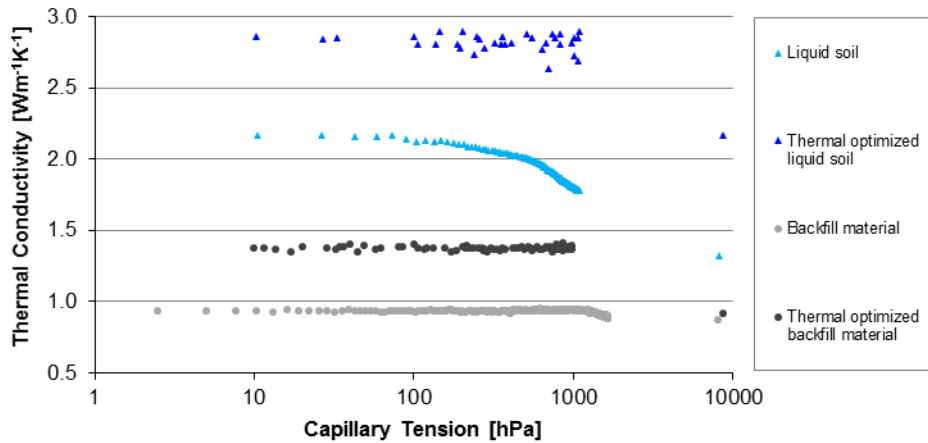


Figure 7: Thermal conductivity of embedding materials as a function of capillary tension.

Figure 7 shows the thermal conductivity in dependence of matrix potential. Compared to the natural soils shown on the right in Figure 5, only a very small change happens in the thermal conductivity with the matrix potential (in the measuring range of the evaporation experiment). A comparison of the poorly graded sand (Fig. 5 Right blue) with the backfill material (Fig. 6 left, light blue) shows significant differences in the magnitude of the thermal conductivity as well as in the drainage behavior, despite comparable main components.

This is due to the cementation at grain to grain contacts and the problems associated with cement hydration refinement of the pore geometry.

3.3 Field investigations

In a first experiment of the recently completed test site, the electrical load on a single cable, which runs through all soil types and the artificial embedding grout, was increased stepwise. The temperatures were monitored by PT100 temperature sensors within the cable and the surrounding soil.

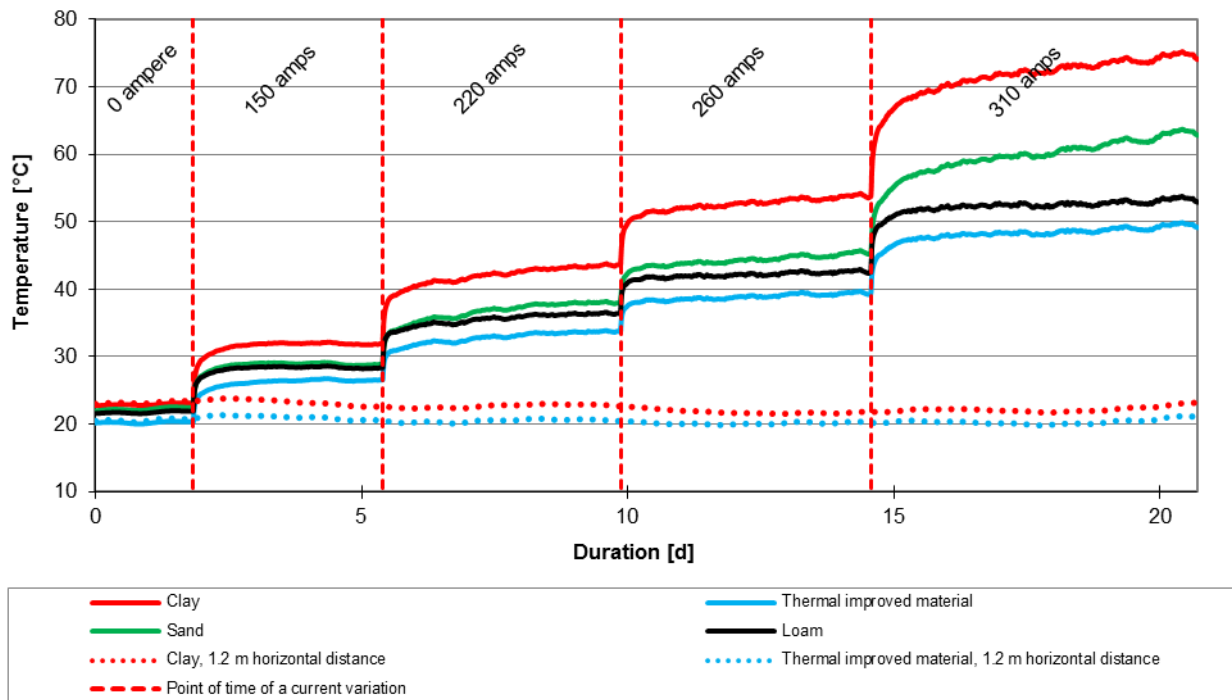


Figure 8: Temperatures of the conductor of a single cable in each field of the test site in continuous lines. The temperatures in 1.2 m horizontal distance to this cable (dotted line) show no thermal influence. The red dashed lines mark the points in time when the current was changed.

After each gradual increase of electric current, a logarithmic increase in the temperature takes place to a maximum value. In the first load step of 150 amperes (Fig. 8), a quasi-stationary temperature level is reached in all materials after about a day. In the following higher electrical load steps, no stationary state is reached. This is associated with a temporally very slow drying process of the materials.

By using a high spatial resolution sensor system, the hydraulic corresponding changes in the embedding materials are investigated in underground cables. These dynamic processes are then used to validate and calibrate simulations. With the help of a spatial high-resolution sensor system, the changes of the hydraulic properties of the corresponding embedding materials are investigated in the corresponding underground cable. These dynamic processes are subsequently used for the validation and calibration of simulations.

4. OUTLOOK

The combined investigation of soils and artificial embedding materials and their thermo-physical and hydraulic properties allows for a more precise prediction of changes in the thermal properties during the operation of geothermal heat exchangers. In order to make long-term predictions for the thermal transferability or optimization of the timing of heat exchange, comprehensive combined testing of soil and embedding material relating to its hydraulic and thermal properties is required.

Renewable energy sources such as photovoltaics or wind power are characterized by variable production and high peak loads. Due to a better knowledge of the thermo-physical and hydraulic properties of the surrounding soil and/or embedding materials, higher loads than assumed by previous standards are possible on a short-term basis without overheating the cable. By using thermally optimized embedding materials with high thermal capacity and thermal conductivity, higher electrical loads and thus higher quantities of emergent heat can be absorbed and dissipated than this is the case in natural soils. Accurate knowledge of soil properties may result in substantial savings in the construction of new cable lines or offer enormous economic advantages by delaying the expansion of already existing networks, as they can be used in a better or more efficient way.

The aim of further studies is to create a statistically representative database of various soil types in order to derive appropriate models for the mathematical description of the relations between thermal conductivity/capillary tension and/or thermal conductivity/water content. Various current mathematical models were developed on the basis of these data and validated against the growing data set. These mathematical descriptions serve as a basis for FEM models for underground heat exchangers. Models of underground cables acting as heat exchangers will be included in the data from the field trial as soon as they have been validated and calibrated.

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REFERENCES

- Blackwell, J.H.: A transient flow method for determination of thermal constants of insulating materials in bulk, *J. Appl. Phys.*, 25, (1954), 137–144.
- Drefke, C., Stegner, J., Sass, I.: Changes of thermophysical and hydraulic properties in unsaturated soils caused by heat transfer, *Proceedings*, European Geothermal Congress, Pisa, Italy, (2013).
- Sass, I., Stegner, J.: Coupled Measurements of Thermophysical and Hydraulic Properties of Unsaturated and Unconsolidated Rocks. *Proceedings*, 37th Workshop on Geothermal Reservoir Engineering Stanford University 2012, SGP-TR-194, Stanford, CA, (2012).
- Schindler, U.: A rapid method for measuring the hydraulic conductivity of partially saturated soils from cores samples, *Arch. Acker- u. Pflanzenbau u. Bodenkunde*, 24, (1980), 1–7.
- Schindler, U., Durner, W., von Unold, G. and Müller, L.: Evaporation Method for Measuring Unsaturated Hydraulic Properties of Soils: Extending the Measurement Range, *Soil Sci. Soc. Am. J.*, 74(4), (2010), 1071–1083.
- Starr, J. L. and Paltineanu, I.C.: Methods for measurement of soil water content: capacitance devices, *Methods of soil analysis*, 4, (2002), 463–474.
- Stegner, J., Drefke, C., Hentschel, K., Sass, I.: Efficiency of buried cables depending on hydrogeological and geothermal properties of trench fill materials. *Proceedings*, European Geothermal Congress, Pisa, Italy (2013).
- Stegner, J., Drefke, C., Sass, I.: New Methods for Determining the Thermophysical and Hydraulic Properties of Unconsolidated Rocks, *Proceedings*, World Geothermal Congress 2015, Melbourne, Australia (2015).
- Wind, G.P.: Capillary conductivity data estimated by a simple method, R.E. Rijtema and H. Wassink (ed.), *Water in the Unsaturated Zone*, *Proceeding*, Vol. 1 Wageningen, The Netherlands, (1968), pp. 166–194