TK04 Application Note

Testing thermal conductivity of soil samples and sand

General

Thermal conductivity of sand materials and soil samples depends on many factors whose knowledge is essential for planning and interpretation of thermal conductivity tests. The most important influences are discussed in this document.

As sand and soil samples belong to the more difficult measuring tasks, the document additionally offers some assistance with the choice of a suitable probe, with sample preparation and with the execution of tests.

Material composition

Porous materials like soil consist of solid grains (the matrix) and pore volume. The thermal conductivity of such a material is determined by the thermal conductivities of both constituents. Matrix grains consisting of pure silica have the highest matrix thermal conductivity of all natural sediments (6.5-12.5 $Wm^{-1}K^{-1}$).

Moisture content

Besides the material composition of the matrix grains, the pore filling also has an important influence on the effective thermal conductivity of a porous material. If the material is dry, the pores are filled with air (thermal conductivity approx. 0.03 $Wm^{-1}K^{-1}$), if it is completely saturated, they are typically filled with water (thermal conductivity approx 0.6 $Wm^{-1}K^{-1}$).

The higher the moisture content, the more pore volume is filled with water instead of air. As the thermal conductivity of water is significantly higher than that of air, the total thermal conductivity of the sample increases with moisture content. The minimum value occurs if the sample is dry, the maximum value is reached if the sample is saturated. Hence thermal conductivity of soil and other porous materials is heavily dependent on moisture content. The maximum can be five or six times the minimum value. The dependency is non-linear, a sample curve measured in our laboratory is appended to this document.

As a consequence, the moisture content of the samples must be known or a well-defined moisture content must be achieved before starting measurements (this also applies to field samples). Already in the planning stage you should decide if your measuring task requires complete registration of the moisture dependency (approx. 7 to 10 tests at different moisture contents), or if a minimum value (dry samples) and / or maximum value (saturated samples) is sufficient.

Density / compaction

It follows from the above that the fraction of pore volume must have an effect on thermal conductivity, too. As the matrix thermal conductivity of sand materials is above the thermal conductivity of both water and air, the total thermal conductivity of a porous sample is the higher, the lower the fraction of pore volume. Hence the thermal conductivity of a porous material increases the better it is compacted (i.e. the higher its density).

The latter is strictly true only for materials with identical composition. While it is possible to artificially increase the density of a natural sand material by adding cement, this measure does not have a significant effect on thermal conductivity. The reason is the matrix thermal conductivity of cement (approx. 1.0 $Wm^{-1}K^{-1}$), which is relatively low compared to natural sediments.

In spite of the high thermal conductivity of quartz, uncompacted dry silica sands only reach thermal conductivity values of approx. 0.3-0.6 $Wm^{-1}K^{-1}$. Usually thermal conductivity can be increased at least by a factor of 1.5 by compacting the material.

When taking samples in the field, the structure of the samples must not be changed. When producing samples in the laboratory, a well-defined degree of compaction must be achieved (the same that will be used later in the planned application). If necessary, the sample material must be tested at different degrees of compaction in order to get an idea of the influence on thermal conductivity in the material in question.

Grain size distribution

Backfills and bedding materials usually are required to have a sufficiently high thermal conductivity. High thermal conductivity values can be achieved by choosing a material with a high matrix conductivity which is then compacted. Materials compact well if they have a wide grain size distribution, i.e. exhibit a high degree of non-uniformity. In order to achieve a sufficiently wide grain size distribution, the material in question must contain a minimum of fines, which can be added by mixing two or more different sands if necessary.

Inhomogeneity of natural materials

As all natural materials are more or less inhomogeneous, you should always take (or produce) several samples and use more than one measuring position per sample. Repeated tests of the same sample (e.g. with different moisture contents) should use the same measuring positions in each cycle.

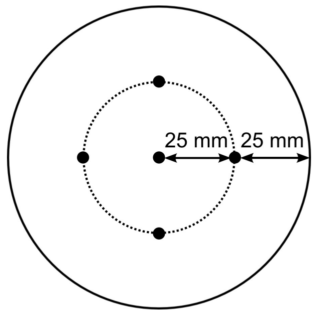
Choice of probe type

In moist samples the water may start to circulate, causing convective heat transport which in most cases renders the test data unusable. Convection is less likely to occur when using the probe for plane surfaces (Standard HLQ) instead of the needle probe (Standard VLQ), because temperature distribution is more stable if the heating source is located on top of the probe, but the sample material could be compacted by the pressure applied to the Standard HLQ in order to ensure good contact. Compaction would increase the thermal conductivity of the sample (see above). Hence we usually recommend to use the Standard VLQ and choose the heating power as low as possible. The Standard HLQ probe can be used only for sufficiently hard or highly compacted samples, which are not compressed further by the necessary contact pressure, i.e. sedimentary rock.

Sample size and measuring positions

For testing soil samples with the needle probe, ASTM D5334 recommends a minimum sample diameter of 51 mm (2 inch) and a sample length of 200±30 mm. The needle probe is then pushed down the sample axis.

When using sampling tubes or rings with a diameter of 100 mm, we recommend to prepare 5 measuring positions (see drawing) and measure at least 3 of them, because natural materials always are more or less inhomogeneous and the contact between probe and sample may not be sufficient for all positions.



Sample preparation

We recommend to use guiding tubes when testing soil samples or sand materials with the needle probe. Guiding tubes are small steel tubes with a tip at the lower end, whose inner diameter matches the dimensions of the Standard VLQ probe. Guiding tubes are available as an option for TK04. The tubes are driven into the sample at the intended measuring positions, the probe is covered with the provided contact fluid and is inserted into the guiding tube. This procedure makes sure that repeated measurements use identical measuring positions, and avoids widening of the holes by repeatedly inserting and removing the needle probe (which would affect the contact between probe and sample). Additionally, the probe is protected against damages caused by coarse or sharp-edged grains or by inserting it into very hard sample materials.

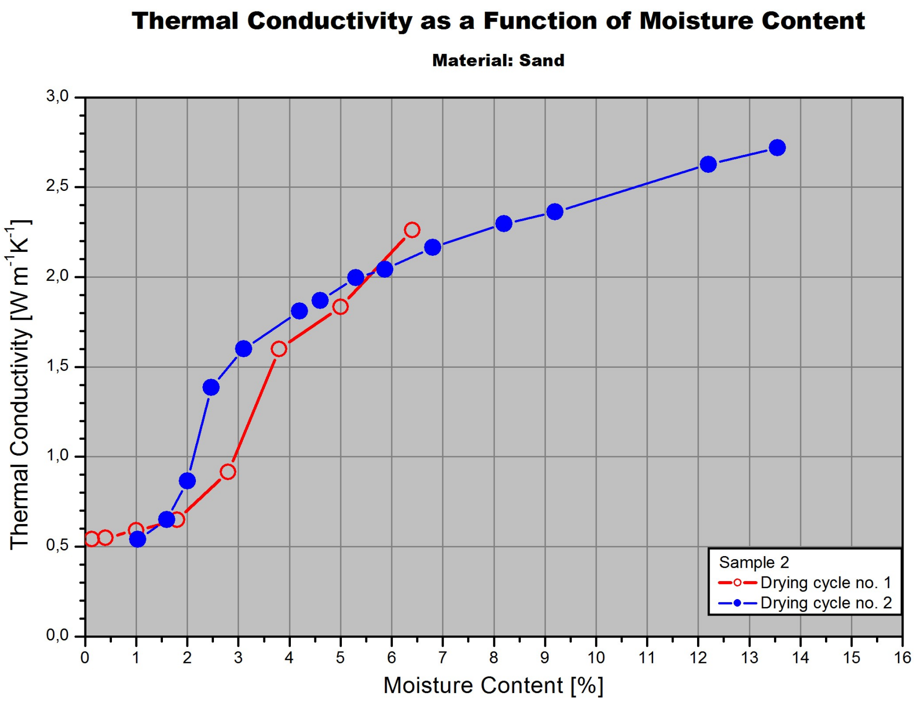
When using the Standard HLQ probe for plane surfaces, no contact fluid is required for moist samples. For dry samples the provided viscous silicon paste should be used (thinner fluids would penetrate into the sample pores and would falsify the value). The sample surface should be plane and free of coarse or sharp-edged components to avoid damaging the probe.

To prevent the water draining out of saturated samples it may be necessary to place them in a water bath during measurements. Please be careful not to immerse the probe connectors, which are splash-proof but not watertight.

Example: dependency of thermal conductivity of silica sand on water content

The diagram shows the thermal conductivity of a typical silica sand plotted versus moisture content (in percent of the moist weight of the sample). Starting from the water content upon delivery, the sample has been gradually dried and thermal conductivity has been determined at different water contents. After saturating the sample, a second drying cycle has been started, measuring thermal conductivity at each drying level. Differences between the two cycles are due to the fact that the sample was taken in situ. Hence moisture distribution is expected to be inhomogeneous during the first cycle due to transport and storage.

Thermal conductivity shows a sharp increase between approx. 1.5 % and 3% water content. While this behaviour is typical for sandy soil samples in general, both the position and slope of the increase (as well as the absolute thermal conductivity values) may vary significantly for different sand materials.



Moisture content is expressed in percent of the moist weight