18033-00
12.2023

METER

APPLICATION NOTE FOR SAMPLE SIZE DETERMINTATION USING TEMPOS HEATED NEEDLE SENSORS

Adapted from the ASTM International Designation: D5334-22, Standard Test Method for Determination of Thermal Conductivity of Soil and Rock by Thermal Needle Probe Procedure sections 7.1.3–7.1.5; 10.1.1.

NOTE: This method from the ASTM standard is for rock and soil, but the principles and methodology are also used for other materials in areas such as food sciences and pharmaceuticals with similar or the same kind of needle probe sensors.

SAMPLE SIZE

TEMPOS sensors measure thermal properties of soil and other materials by injecting a heat pulse into the material using a needle with a heater and a temperature sensor inside a soil sample. Heat moves out from the needle during the measurement with a kind of cylindrical front. The radial distance of that front from the needle depends on the radius of the needle, the time over which measurements are taken, and the thermal diffusivity of the sample. For best measurement accuracy, the radius of that cylinder should stay within the sample being measured for as long as the measurement takes. That radius is therefore the minimum sample size that should be used.

Figure 1 is from ASTM D5334-22. It shows three curves generated for probe sizes selected to span typical needle radii of TEMPOS probes. The minimum sample radius is plotted vs. the product of thermal diffusivity and measurement time. To use the graph, diffusivity and measurement time must be known. Probe radius has little effect.

Ensure the sample or specimen is large enough to cover the sensor probe entirely. This prevents ambient temperature fluctuations outside of the sample from interfering with the accuracy of the reading. The sample thermal diffusivity determines how fast heat can travel through. The time it takes for heat to travel through the sample is determined by thermal diffusivity and not the thermal conductivity of the sample or differences in temperature at the source. Equation 1 uses the thermal diffusivity (D) of the specimen, the time duration (t) of the reading, including heating and cooling if measured, and the radius of the needle (a). This assumes that there is a 99% heat reduction at distance r small enough to:

1. Have a negligible effect on the reading
2. Have curves delineating the minimum size of the specimen (the radius and approximate length beyond the end of the needle) that can be derived empirically from Equation 1 parameterized by the thermal diffusivity (D) of the specimen

The time duration (t) of the reading, including heating and cooling if provided, and the radius of the needle (a) are also needed for this equation (Equation 1).

$$\Delta T = -\frac{Q}{4\pi\lambda}\mathrm{Ei}\left(\frac{-r^2}{4Dt}\right) \quad 0 < t \leq t_i \qquad \textbf{Equation 1}$$

Figure 1 plots three curves generated for probe sizes selected to span typical needle radii (using Equation 1).

These curves assume the product of the sample thermal diffusivity (D) and reading time duration (t) on the x-axis, so the minimum specimen radius can be read off the y-axis. In addition, a power law equation approximates the results for each curve. For other needle radii, interpolation or generating a new curve may be appropriate.

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$r=3.971(Dt)0.4382 \quad a=2mm$

$r=3.5453(Dt)0.4526 \quad a=1.2mm$

$r=3.2392(Dt)0.4623 \quad a=0.64mm$

where:

r = distance from the heated needle (mm) (minimum radius of the specimen),

D = thermal diffusivity of the specimen (mm$^2/s$)

t = time from the beginning of heating to the end of the test (s), and

a = radius of the needle

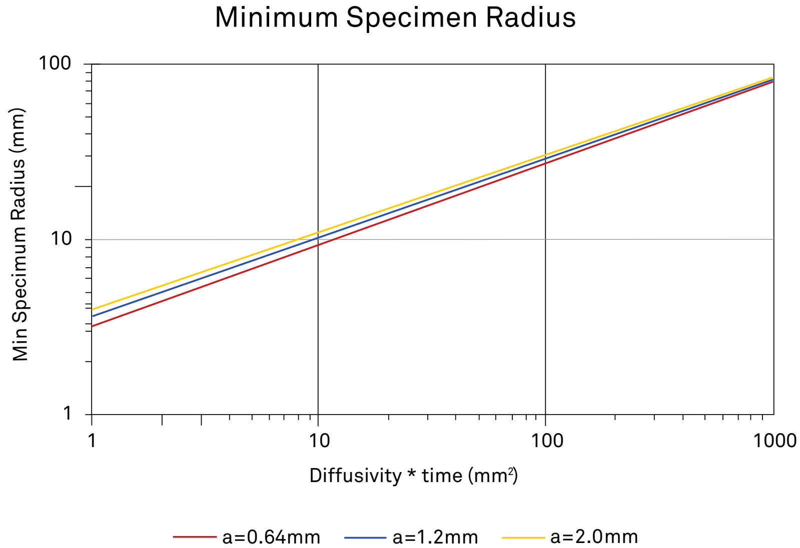

Figure 1 Minimum radius of a specimen

THERMAL DIFFUSIVITY

There are many ways to estimate the specimen's thermal diffusivity. Some instruments are designed to directly measure thermal diffusivity. Alternatively, it can be calculated from a previous measurement of the thermal conductivity and the specimen's volumetric heat capacity ($P_S C_s$) in $MJ/(m^3K)$ according to Equation 2:

$$D = \frac{\lambda}{\rho_S c_S} \qquad \textbf{Equation 2}$$

where:

D = thermal diffusivity (m^2/s)

λ = thermal conductivity ($W(mK)$)

P_S = density (kg/m^3), and

C_s = specific heat ($J/(kgK)$)

Another option is to estimate thermal diffusivity from a graph of thermal diffusivity values, such as the one in Figure 2.

Thermal diffusivity is the ratio of thermal conductivity to volumetric specific heat. The TEMPOS SH-3 probe measures it, but a rough estimate is available just by looking at typical values. Thermal diffusivity of soil depends on water content, density, and mineralogy. Figure 2 (Campbell and Norman, 1998) shows typical values. The sand is so high because it is quartz, which has a much higher thermal conductivity than other soil minerals.

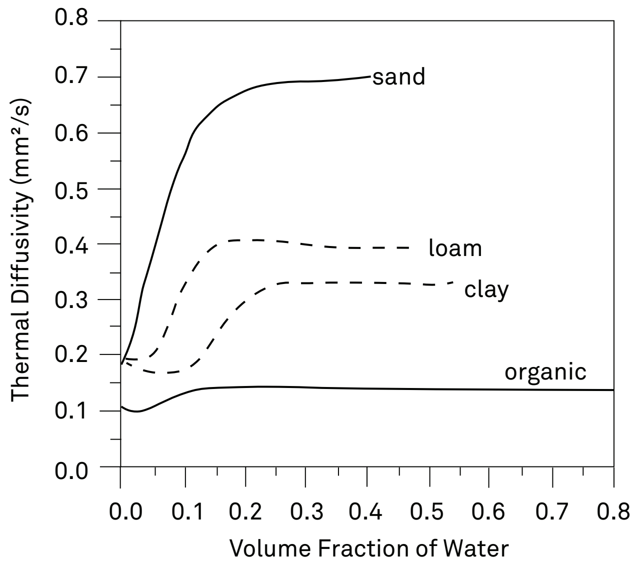

Figure 2 Thermal diffusivity values for select soil types

The specimen or sample must be greater than or equal to the length of the sensor needle. For accurate readings, it is better if the sample is larger than the sensor needle length. If the sample and needle are close to the same length, any material in contact with the end of the sample may adversely affect the measurements (e.g., soil sample containers or tubes commonly made of glass or metal). The higher the thermal conductivity of the materials in contact with the sample, the more adversely it affects the reading. To prevent this, add to the sample length. The amount needed to avoid adverse readings is roughly the minimum radius of the sample. Adding the sample's minimum radius to the sample's length should be sufficient to ensure accurate readings. Another way to make sure the readings are correct is to place the needle as close to the middle of the sample as possible. This will create the most space possible between the needle and the material holding the soil sample for optimal readings.

NOTE: Specimen dimensions assume the sample is cylinder-shaped with the needle inserted along the cylinder's axis. As long as the sample size can fully surround the radius and length specified, the shape does not matter.

MEASUREMENT TIMES

The other information we need to compute the minimum sample size is the measurement time. Table 1 shows heating and measurement times for all the TEMPOS sensor probes.

Table 1 Heating times for TEMPOS sensors

Sensor	Heating Times
KS-3	1 min
TR-3/TR-4	1 min in reading mode
TR-3/TR-4 ASTM/IEEE, option 1	5 min in reading mode, heats for first 2.5 min
TR-3/TR-4 ASTM/IEEE, option 2	10 min in reading mode, heats for first 5 min
SH-3	2 min in reading mode, heats for first 30 s, cool for 90 s
RK-3	1 min in reading mode
RK-3 ASTM/IEEE, option 1	5 min in reading mode, heats for first 2.5 min
RK-3 ASTM/IEEE, option 2	10 min in reading mode, heats for first 5 min

The longest measurement times are 10 minutes, or 600 seconds. The largest sample radius that would ever be needed is for a wet sand soil sample with a diffusivity of 0.7 mm^2/s. Using Figure 1 would enter at 0.7 x 600 = 420 mm^2 and get a radius of about 40 mm. For a KS-3 with a 1 min (60 s) heating time the radius (from Figure 1) would be about 20 mm. For organic materials with a diffisivity of 0.15 mm2/s, and a measurement time of 60 s, enter Figure 1 with 0.15 x 60 = 9 mm2 and get a sample radius of about 10 mm. Dry soils would be about the same. So, for all soil type materials and TEMPOS probes, the minimum sample radius ranges from 10 to 40 mm.

For more details on working with soil samples and needle probe sensors, refer to the ASTM standard and METER user manuals for TEMPOS (meter.ly/tempos-support).

REFERENCES

American Society for Testing and Materials (ASTM) International. 2022. Standard Test Method for Determination of Thermal Conductivity of Soil and Rock by Thermal Need Probe Procedure. [accessed 2022 May 1]. https://www.astm.org/d5334-22ae01.html.

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