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TNO report

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Thermal conductivity, density and volumetric heat capacity of soil samples

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Contents

1 Introduction

For an offshore wind farm project in the North Sea Fugro carries out site investigations. A client of Fugro (RVO) requested the determination of thermal conductivity, volumetric heat capacity and density of soil samples. At the request of Fugro, the samples were saturated with water, in order to create a slurry. This is in accordance with the appearance of the material in situ: as a slurry.

Of these slurries, the density was determined by measuring-cylinder-method. This method consists of weighing an amount of slurry and measuring the volume of this amount by measuring cylinder. The quotient of these two values results in the density of the slurry.

After density measurement, the same slurries were used in determining both thermal conductivity and volumetric heat capacity, by applying the Hot Disk Thermal Constants Analyser. Measurements with this instrument are based on the Transient Plane Source method. With this method a transiently heated plane sensor is used, which consists of an electrically conducting pattern in the shape of a double spiral. When performing a measurement, a plane Hot Disk sensor is fitted between two parts of the sample. By running an electrical current, strong enough to increase the temperature of the sensor up to several degrees, and at the same time recording the resistance (temperature) increase as a function of time, the Hot Disk sensor is used both as a heat source and as a dynamic temperature sensor. From this temperature increase the thermal properties of the surrounding medium (sample) are calculated.

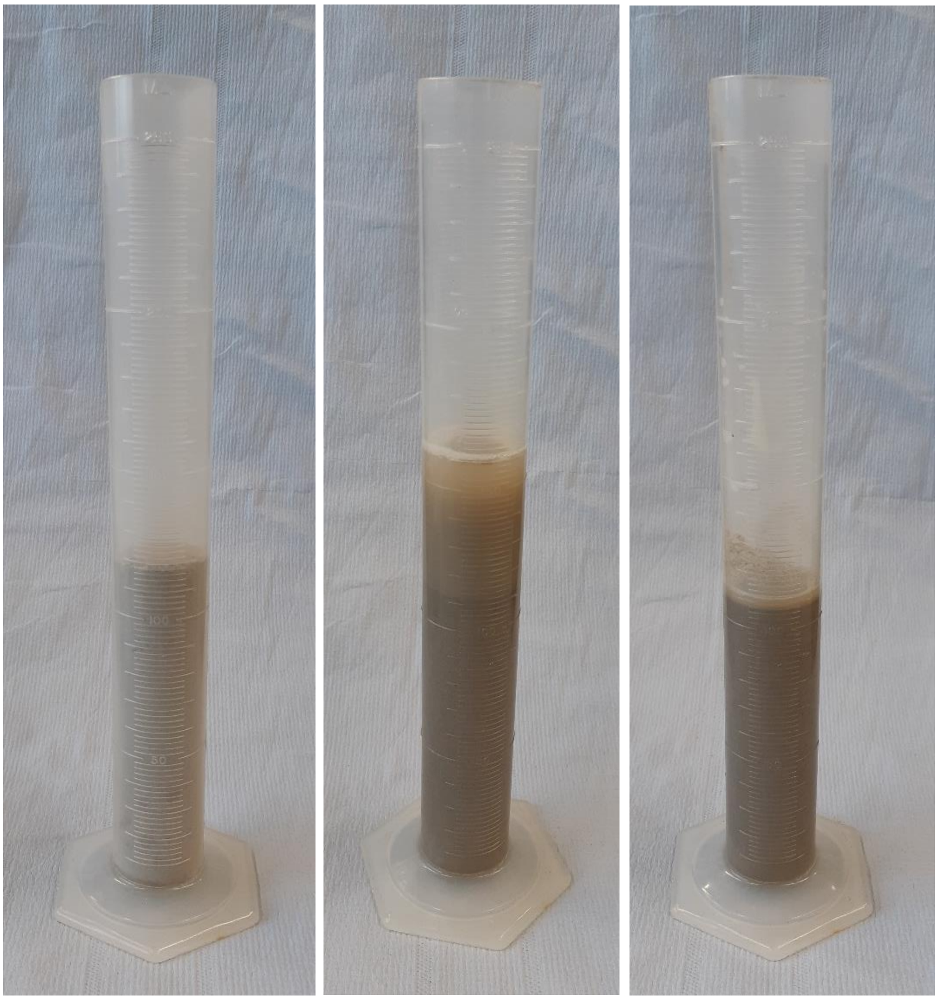
For the measurements of these kind of samples a dedicated sample cell was constructed within this project. The design of this sample holder was based on the powder/paste sample holder as described in the instrument manual. Only the dimensions were adapted to the particular measurement parameters.

2 Experimental

2.1 Density measurements

A total of 29 samples were sent to ECN-TNO by Fugro. Of this set of samples 27 were delivered in the form of dry sand, and 2 samples were delivered as slightly moist, clay-like material (from TU Delft). Of the dry sand samples Fugro indicated that 5 of them should not be measured at all, so in total 24 samples were measured.

Of the dry samples around 180 gram of material (as received) was loosely deposited into a 250 ml plastic measuring cylinder. Any present large shells were removed. the cylinder was bounced on a table from a height of around 5 cm, for three times. After this, the volume was read from the measuring cylinder and the weight of the sand was determined (figure 1a). This step provides the dry density (TNO) of the sample material as received.



a ***b*** ***c***

Figure 1 Volume of dry sand (a), over saturated slurry (b) and saturated slurry (c)

To the sand-containing cylinder an excess amount of demineralized water was added and this mixture was manually mixed thoroughly. After this, the sand was allowed to settle for 5-10 minutes (figure 1b) and the excess water was removed by decanting, so a saturated mixture of sand and water (slurry) was created (figure 1c). This slurry was weighed and the volume was determined from the measuring cylinder, leading to the bulk density of the slurry mixture.

With the *TU Delft* samples it was not possible to measure the density with the procedure as described above. The delivered samples were impossible to mix properly with excess water and too clay-like to fill the measurement cylinder without enclosing a large amount of air. This makes a proper volume measurement impossible.

2.2 Thermal properties measurements

After measurement of the density the slurry was then brought into one half of the Hot Disk sample cell (figure 2a and 2b). The TU Delft samples were brought into the sample cell as received. The internal diameter of the sample cell was 50 mm and the height of the lower sand bed was 12 mm. The sensor was placed on top of this sand bed (figure 2c), followed by the other half of the sample cell (figure 2d) and approximately the same amount of slurry (hight upper sand bed: approx. 12 mm) was added to the sample cell (figure 2e). The cell was placed upright (figure 2f) and the Hot Disk measurement was performed after 15 minutes of stabilization time. During the filling procedure only a few drops of water (< 200 mg) were lost.

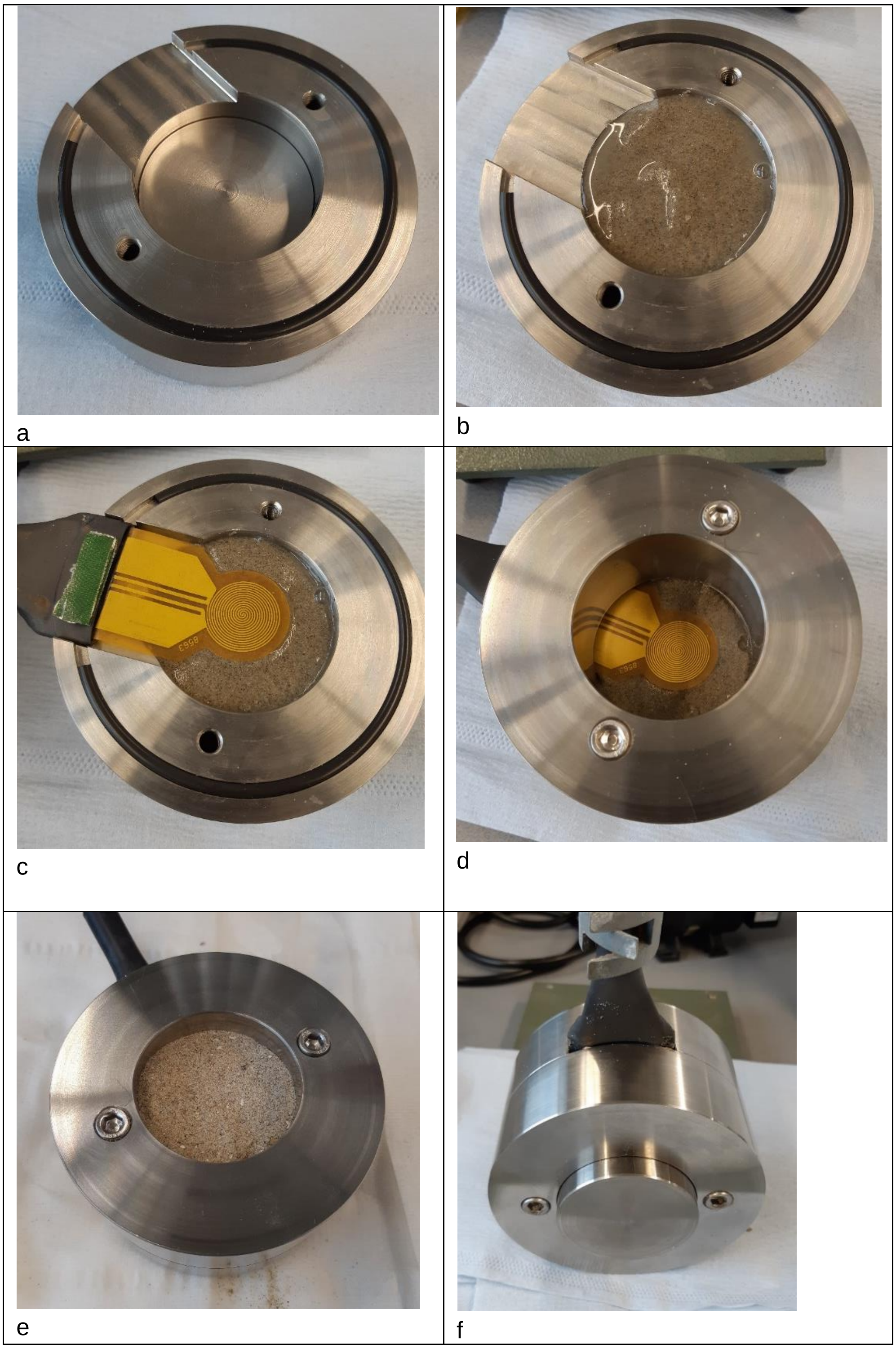


Figure 2 Sequence of the filling procedure of sample cell

For the measurement the following settings were used:

- Sensor: 8563 (radius 9.868 mm)
- Heating power: 750 mW
- Measurement time: 20 s.

These settings lead to a typical transient graph as presented below. This transient curve describes the temperature increase of the sensor during the measurement time of 20 seconds. Only the section between (in this case) 2 seconds and 20 seconds is used to calculate the thermal properties.

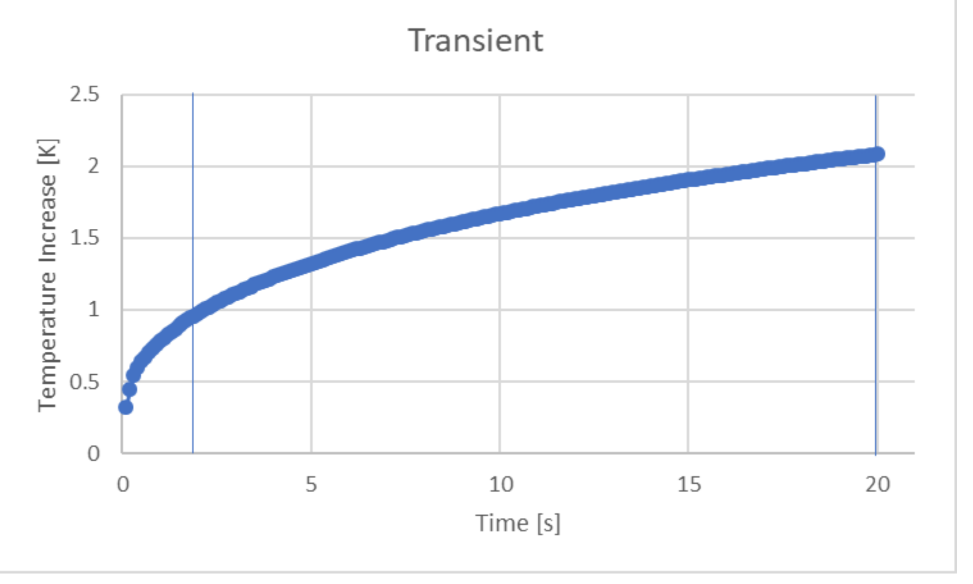


Figure 3 Typical transient curve

3 Results

In table 1 an overview of the results of the densities measured by TNO (wet density as in figure 1c, dry density as in figure 1a)) as well as the results measured by Fugro.

Table 1 Results of the density measurements

Sample ID **Borehole**	**Sample**	**Depth** **[m]**	**Dry Density Fugro [kg/l]**	**Wet Density TNO [kg/l]**	**Dry Density TNO [kg/l]**
HKN02-BH-SA	05BagA	3.5	1.68	1.72	1.43
HKN06-BH-SA	04BagA	3	1.69	2.00	1.55
HKN10-BH-SA	04BagA	3	1.49	1.87	1.41
HKN21-BH-SA	03BagA	2	1.58	1.96	1.47
HKN26-BH-SA	02BagA	1	1.64	1.94	1.50
HKN26-BH-SA	05BagA	4	1.62	1.86	1.40
HKN27-BH-SA	05BagA	3	1.79	2.05	1.65
HKN31-BH-SA	03BagA	2	1.4	1.94	1.54
HKN36-BH-SA	03BagA	1.5	1.67	1.97	1.57
HKN36-BH-SA	04BagB	2.9	1.45	1.84	1.34
HKN41-BH-SA	06BagA	4.5	1.4	1.77	1.31
HKN46-BH-SA	04BagB	2.8	1.55	1.95	1.51
HKN47-BH-SA	04BagA	2	1.45	1.97	1.61
HKN48A-BH-SA	02BagB	3.05	-1)	1.90	1.43
HKN56-BH-SA	05BagA	3	1.48	1.88	1.35
HKN58-BH-SA	04BagA	3	1.58	1.95	1.50
HKN65-BH-SA	02BagA	1	1.64	1.97	-1)
HKN65-BH-SA	04BagA	3	1.56	1.91	1.47
HKN67-BH-SA	02BagA	0.5	1.57	1.98	1.56
HKN67-BH-SA	04BagB	2.8	-1)	1.69	1.16
HKN72-BH-SA	04BagA	3	-1)	1.92	1.44
HKN75-BH-SA	04BagA	3	-1)	1.94	1.43
TUDelft	1	12.35	1.63	-3)	-2)
TUDelft	2	11.05	1.89	-3)	-2)

1) *Not measured*
2) *Samples delivered wet*
3) *Thick clay: no proper measurement possible*

In Table 2 an overview is given of the results of the thermal properties of the samples.

Table 2 Results of thermal properties

Sample ID **Borehole**	**Sample**	**Depth** **[m]**	**Thermal Conductivity [W/mK]**	**Thermal Diffusivity [mm²/s]**	**Volumetric Heat capacity [MJ/m³K]**	**Thermal Effusivity [Ws$^{1/2}$/(m²K)]**
HKN02-BH-SA	05BagA	3.5	1.614	0.3874	4.167	2593
HKN06-BH-SA	04BagA	3	2.569	0.9361	2.745	2656
HKN10-BH-SA	04BagA	3	2.401	0.8571	2.801	2594
HKN21-BH-SA	03BagA	2	2.211	0.839	2.635	2414
HKN26-BH-SA	02BagA	1	2.597	0.9734	2.668	2633
HKN26-BH-SA	05BagA	4	2.342	0.8564	2.734	2530
HKN27-BH-SA	05BagA	3	3.063	1.275	2.402	2713
HKN31-BH-SA	03BagA	2	2.755	1.041	2.647	2701
HKN36-BH-SA	03BagA	1.5	2.572	0.9997	2.573	2573
HKN36-BH-SA	04BagB	2.9	2.228	0.8068	2.762	2481
HKN41-BH-SA	06BagA	4.5	1.836	0.6702	2.739	2243
HKN46-BH-SA	04BagB	2.8	2.446	0.8884	2.753	2595
HKN47-BH-SA	04BagA	2	2.92	1.124	2.599	2755
HKN48A-BH-SA	02BagB	3.05	2.331	0.8543	2.728	2522
HKN56-BH-SA	05BagA	3	2.917	1.767	1.651	2195
HKN58-BH-SA	04BagA	3	2.364	0.4851	4.874	3395
HKN65-BH-SA	02BagA	1	2.267	0.9071	2.499	2380
HKN65-BH-SA	04BagA	3	2.283	0.8392	2.72	2492
HKN67-BH-SA	02BagA	0.5	2.245	0.8176	2.746	2483
HKN67-BH-SA	04BagB	2.8	1.766	0.5552	3.181	2370
HKN72-BH-SA	04BagA	3	2.214	0.7851	2.819	2498
HKN75-BH-SA	04BagA	3	2.246	0.8542	2.629	2430
TUDelft	1	12.35	1.689	0.5909	2.859	2198
TUDelft	2	11.05	1.836	0.7306	2.512	2147

4 Signature

Petten, 5 March 2019

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ECN part of TNO

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