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ScienceDirect

Energy Procedia 125 (2017) 671–677

Energy Procedia

www.elsevier.com/locate/procedia

European Geosciences Union General Assembly 2017, EGU
Division Energy, Resources & Environment, ERE

Laboratory Measurements of Gravel Thermal Conductivity: An Update Methodological Approach

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Abstract

Direct measurements of gravel thermal properties are usually quite challenging to be performed in laboratory, due to the very coarse sediments size. As a consequence, the reference thermal values provided by literature for gravels are quite limited and dispersed. A guarded hot plate Taurus Instruments TLP 800, usually used for measuring the thermal conductivity of buildings materials, was slightly modified in order to measure the thermal conductivity of some gravel samples. The tests were performed both in dry and wet conditions. The paper presents the first obtained results.

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Keywords: Cheap-GSHPs; gravel; thermal conductivity; guarded hot plate.

1. Introduction

The EU Horizon 2020 project entitled “Cheap-GSHPs: Cheap and Efficient Application of Reliable Ground Source Heat Exchangers and Pumps” (grant agreement No. 657982) focuses on improving the efficiency and the

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Peer-review under responsibility of the scientific committee of the European Geosciences Union (EGU) General Assembly 2017 – Division Energy, Resources and the Environment (ERE).
10.1016/j.egypro.2017.08.287

safety of shallow geothermal systems and on the reduction of their installation costs. Moreover, the project develops a Decision Support System (DSS) and other design tools for the newly developed technologies compared to other low enthalpy geothermal systems. In the DSS the local geological aspects as well as the feasibility and economic assessments are evaluated, by considering different plant set-up options, selection, design, installation, commissioning and operation. These tools will be made publicly available on the web to users (see the web site), including comprehensive training to lower the market entry threshold.

In order to optimize the total probes length design, one of the most important aspects to be taken into account during the design phase of a Ground Source Heat Pump (GSHP) system is a good estimation of the heat exchange capacity of the ground where the probes are inserted. The evaluation can be performed indirectly on site, by deriving the thermal exchange capacity from the interpretation of the outputs obtained from the Thermal Response Test (TRT) carried out on a testing probe already built. These well-developed methodologies are usually employed [1,2] to estimate a global value of the heat exchange capability of the whole probe-ground system. It is governed firstly by the thermal properties of the geological materials that constitute the entire stratigraphy intersected by the probe; and, in addition, it is also influenced by the heat exchange advection processes in the aquifers due to the groundwater flow. Secondly, the global heat exchange capability value also depends on the thermal properties of the pipes' materials and of the grouting used to fill the borehole as well as on the heat carrier fluid flow conditions inside the pipes (turbulence/Reynolds number) and on the quality of the borehole grout sealing.

Another option is to evaluate directly the local ground heat exchange capability by defining the thermal properties of each layer or deposit intersected by the probe [3,4]. That way, it is necessary to collect samples from the cores extracted at the site and to measure directly the thermal properties of each deposit.
Alternatively, after a definition of the local geological sequence intersected by the probe, in first approximation, it is possible to assume the thermal properties values recommended in literature. Usually, the underground materials' conductivity values reported by regulations and guidelines are quite generic mainly owing to the very different geological (consolidation status, moisture content and saturation, compaction level, etc.) conditions as well as to the high variability of mineralogical composition of materials belonging to the same granulometric category.

In order to provide a more defined database of the ground thermal properties to the DSS and to improve the definition of thermal properties reported in literature, one of the objectives of the Cheap-GSHPs project is to build up a dataset of thermal properties of geological materials (hard rocks and unconsolidated sediments), by implementing literature values as well as collecting thermal properties directly measured on samples coming from several European sites. The database will include gravels as well as sands, silts and clays, and finally hard rocks thermal parameters, in order to improve the definition of the thermal properties of defined granulometric sub-categories of sediments. Where available, the database will contain also the measuring device and method employed in the test, and the related geotechnical (granulometry, Atterberg Limits, etc) or petrophysical information (density, porosity, etc).

2. Gravel thermal properties measurements

Direct measurements of gravel thermal properties are quite challenging mainly due to technical issues related with the very coarse sediment size, which impedes an appropriate physical contact between the material and the traditional measuring sensors. In addition, the variability of the mineralogical composition of the polygenic samples in many cases requires a quite large volume of geological material to be involved in the measurement procedure, in order to obtain representative thermal properties values. Considering the traditional sensors, the gravel sediment size and the presence of the large interstitial voids close up a continuous physical contact between the material and the measuring sensor (usually needle or plane probes). However, an appropriate physical contact between the sediment and the sensor is necessary and, in case of gravel, it is not achieved due to the coarse dimensions of the clasts.

In addition, the effective thermal conductivity of a porous media depends on the thermal conductivity of the solid grains [5] and a sample of gravel could be composed by clasts of different mineralogical and lithological composition due to their different origins. For this reason, the measurement has to involve a quite large volume of unconsolidated sediments in order to reach the elementary representative volume. In the past, some researchers proposed original devices for measuring gravels' thermal conductivity [6,7]. Barrie W. Jones (1988) [6] for the first time developed a probe method of measuring thermal conductivity of gravel and tested it on an unconsolidated pebble bed consisting of graded river pebbles (equivalent spherical particle diameters 24±7 mm, bulk porosity of 0.396). He obtained a value of thermal conductivity equal to 0.55 ±0.02 Wm−1K−1 at 25 °C (dry conditions), increasing slightly with temperature [6]. More recent researchers [7] highlight that the gravels thermal conductivity is more affected by the clasts mineralogical composition rather than by the dimensions of the clasts themselves. They compared the thermal conductivity measured on gravel samples with similar angular shaped clasts dimensions (quite homogeneous) but different mineralogical compositions. The tests were repeated for three different granulometric classes of the pebbles. The tested samples were constituted by carbonatic (Calcite 87%, Dolomite 11%), granitic (Quartz 22%, Plagioclase 25%, Kalifeldspar 22% and Biotite 29) and rhyolitic lava clasts. Obviously, the latter sample was characterized by a higher porosity (around 0.7) than the others (both around 0.5). In dry conditions, the lava stones showed the smallest thermal conductivity (ca. 0.14 Wm−1K−1), while the carbonates presented the highest values (ca. 0.23 Wm−1K−1). The authors concluded that there was no significant dependence on grain size, since the conductivities with the respective measurement errors overlap by more than 70%. However, he observed a significant dependence on the porosity [7].

The reference thermal values obtained from laboratory measurements provided by the most diffuse guideline for gravels are quite limited and present a large range of values, as reported in table 1.

Table 1. Thermal conductivity reference values extracted from literature (i.e. VDI 4640 [8]).

Sediment category	Thermal Conductivity (as indicated in VDI 4640) Min [W/mK]	Max [W/mK]	Recommended value [W/mK]
Gravel dry	0.4	0.9	*0.4*
Gravel water-saturated	2.0	3.0	*2.4*
Sand dry	0.3	0.9	*0.4*
Sand moist	1	1.9	*1.4*
Sand water-saturated	2.0	3.0	*2.4*
Clay/silt dry	0.4	1.0	*0.5*
Clay/silt water-saturated	1.1	3.1	*1.8*
Till/loam	1.1	2.9	*2.4*
Peat, soft lignite	0.2	0.7	*0.4*

2.1. The new methodology proposed

In order to overcome the issues related to the size of the gravel clasts and the difficulties to get a continuous contact surface between the sample and the measuring sensor, a new device is tested. In addition, the proposed device allow analyzing a quite large volume of unconsolidated sediments, therefore this methodology also allow taking into account the mineralogical composition variability.

The newly proposed device consists in a guarded hot plate Taurus Instruments TLP 800, usually used for measuring the thermal properties at the FISTEC laboratory (Environmental Technical Physics Laboratory) of the University of IUAV in Venice (Italy). This device is usually used to measure thermal properties of building materials according to the specific regulations ASTM C177-85[9] and EN 12667[10] by means of a measuring plate of 0,8 x 0,8 m. It is based on a steady-state method. It works imposing and maintaining a constant temperature difference usually equal to 10 °C between three parallel plates in a symmetric configuration with the cold one in the central position (usually at 15 °C) and the two hot plates above and below (usually at 25 °C). Two samples of the same material are placed in between. That way, a one directional heat flux is established through the samples, and the thermal conductivity is measured every minute. The test stopped when the thermal equilibrium is achieved and the subsequent measured values of thermal conductivity are stable; at a given temperature, the series of measurements needed to obtain the validated value lasts about 6-7 hours.

In order to finalize the thermal measurements for gravels, some changes have been made to the standard setup. Firstly, a Plexiglas box of 50 x 50 x 6 cm has been built, in order to contain the gravel sample. The volume of the sample-box allows involving a representative volume of unconsolidated material, therefore including all the different present lithologies and minerals in the sample. Despite the device typically works in a symmetric way with a ‘double cold plates’ configuration, for testing the gravel samples the lower plate was neutralized by a dummy heating sample and only the higher cold plate and the hot plate were used (Fig. 1). The temperature difference imposed between the hot and the cold plate is lowered from the standard value to 5K, in order to minimize the convective contribution on the measured thermal values.

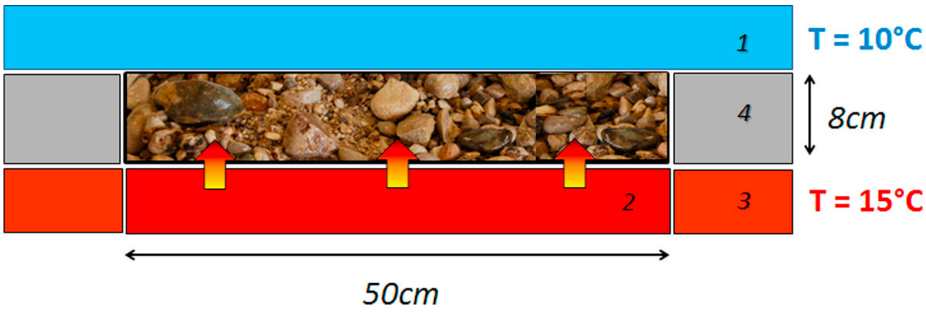


Fig.1. The guarded hot plate device tested for measuring thermal properties of gravels. 1: cold plate; 2: hot plate; 3: protection material to the hot plate; 4: protection ring of insulation material (guard), used to impose a one-dimensional heat flux through the sample.

In contrast with transient methods, the steady-state methods involve the simultaneous measurement of the steady-state heat flux and temperature gradient through the tested sample. The guarding system, here constituted by a protection ring of insulating material, is required to minimize the edge or end effects in order to achieve a mono-dimensional heat flux [5].

In figure 2 some phases of the proposed methodology are depicted.

Fig.2. Several phases of thermal measurements on gravel samples by using the proposed device. a - b) The gravel sample is inserted into the box; c) After closing the box cover, the thermal sensors are installed; d) The refrigerant system is positioned in order to maintain the imposed temperature in the cold plate.

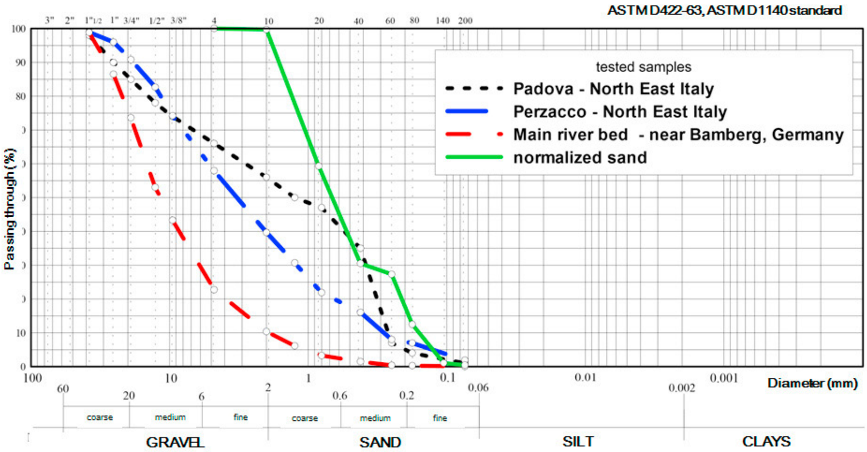
2.2. Results

First of all the device was tested on a sample of normalized sand (CEN Standard sand CEN-EN 196-1) in order to use it as a reference material. Starting on dry condition, the thermal measurements were repeated at constant mean temperature (20 °C) by adding well known amount of water. Figure 3a shows the granulometric curve obtained by sieve analysis. The density is equal to 2.65 Mg/m^3 and silica (98.28%) represents the dominant mineral. In figure 3b the thermal conductivity is depicted as a function of the amount of water added in the voids of the sample (porosity of the sample in the testing condition 0.2); the first value can be referred to as 'dry' condition (λ = 0.38 W/mK), while the last one represents the 'nearly saturated' condition (λ = 1.5 W/mK). Hence, a preliminary evaluation of the results obtained by using the modified single guarded hot plate has been performed by comparing the values obtained for the Standard sand with the ones acquired on the same sample by means of the needle probe sensor of the thermal conductivity analyzer ISOMET 2114. The line heat source method applied in the needle probe (transient method) is usually satisfactory for the determination of effective thermal conductivities of unconsolidated sands under a variety of test conditions. The measurements are rapid and reproducible within one or two percent [5]. The values obtained with the linear probe were λ = 0.41 W/mK in dry condition and λ =1.72 W/mK in 'nearly saturated' condition.

A second series of tests was conducted on several gravel deposits samples collected around Europe. These measurements are already in progress and, up to now, only three gravel samples have already been concluded. The samples were collected in Northern Italy in the Po plain and in Germany at the Main River (Northern Bavaria). The samples are defined by means of the specific weight, and the visual description of the clasts lithologies (table 2) combined with the sieve analysis depicted in figure 3a. The measurements were performed at a constant mean temperature of the sample of 20°C, firstly in dry conditions and then by adding known amounts of nebulized water up to obtain wet conditions (see Fig.3b). The water was added very slowly with a nebulizator until the sample was no more able to receive other water.

Table 2. Visual description of the lithologies in the gravel samples

Sample	*Visual description*	*Specific weight [kg/m³]*	*Porosity*
Main river bed – near Bamberg. Bavaria, Germany	Heterogeneous gravel, poorly sandy – polygenic clasts, mainly carbonatic composition (some clasts of quartz) – clasts from sub-rounded to plates with a maximum diameter of 5-6 cm.	1891	0.19
Perzacco - Verona-North East Italy (5-10 m)	Medium to fine sandy gravel – mainly calcareous clasts - some harder cemented layers. Maximum diameter equal to 4 cm.	1838	0.17
Padova - North East Italy(Po plain) (121 – 129.5 m)	Gravelly sand – mainly carbonatic composition with some loosely cemented layers – mainly sub-rounded clasts. Maximum diameter 5-6 cm.	1856	0.17

a) 

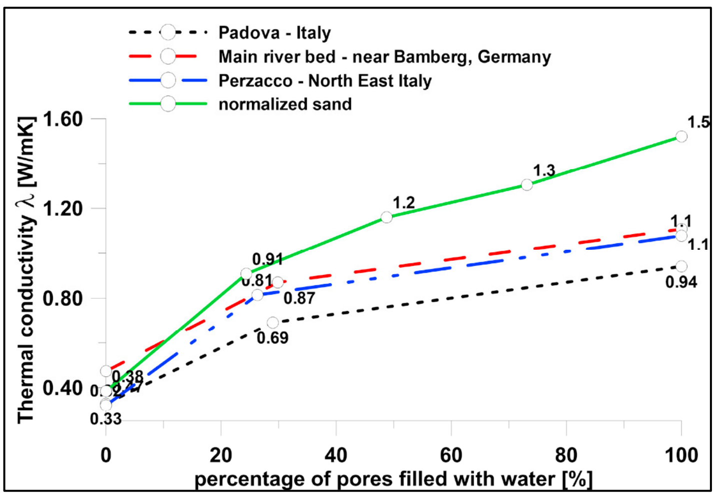
b) 

Fig.3. a) Granulometric curves of the tested 'normalized sand' and of the gravel samples. b) Thermal conductivity values obtained in dry and wet conditions.

Due to the addition of water, many difficulties were encountered. It is known that the measurements performed with steady-state methods require a relatively long time to attain the thermal equilibrium. In case of porous media, containing partial liquid saturation, the application of the temperature gradient for a long period of time results in a non-uniform liquid saturation distribution due to the effects of thermal osmosis [5]. Hence, the thermal conductivity measured in such conditions could be affected by the size of grains and voids in the sample tested and by the temperature gradient applied between the two plates because in large voids, as in case of gravels, local convection motions could be established. For this reason the temperature gradient imposed was maintained at the minimum value feasible for the device used.

Anyway, despite the moisture distribution in the sample should be considered inhomogeneous (although the water was added by means of a nebulizer), the measured thermal conductivity values show a clear increase with the percentage of pores' volume filled with water, according with literature [5-8,11,12]. The values in wet condition are two or three times the ones in dry condition. It is interesting to note that the increase is mainly achieved at the first step of added water.

The normalized sand reaches higher values than the other samples, probably due to the very high silica content. From these first results no clear signals arise about the thermal conductivity dependence on mineralogical origin of the clasts or on gravels dimensions, due to the quite low number of tested samples.

The experimental values obtained in these tests are representative of the ‘static’ situation assessed in laboratory, where the sample is constrained into a box. Indeed, at the tests site scale, the TRT interpretation provides very high thermal conductivity values for gravel deposits. These values are usually higher than the conductive component because they are strongly affected by regional groundwater flow and the advective heat transport [13].

3. Conclusions

Thermal conductivity of gravel samples have been measured in dry and wet condition, by slightly modifying a commercial testing device usually used for building materials. The proposed device operates as a single guarded hot plate. The large dimensions of the plates allow overcoming the issues related to laboratory measurements of gravels' thermal parameters. In addition, the proposed methodology also solves the issues related to the high mineralogical variability of the gravel consisting lithologies, by handling a more representative volume of clasts.

The proposed device provides interesting results, both on dry and wet samples. The experimental data show an increase of the thermal conductivity values with the increasing of water content in the pores.

Further tests are currently underway in order to expand the dataset of experimental results and study the influence of granulometry, mineralogy, porosity and moisture on the thermal conductivity of gravels. Moreover, the coming experimental tests are going to study the variations of gravel thermal conductivity parameters at different temperatures.

Acknowledgements

Cheap-GSHPs project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 657982. The authors want to gratefully thank Mr. Mario Celebrin and Mr. Massimiliano De Bei of FISTEC laboratory of IUAV – Università di Venezia. Authors also thank Mr. Diego Mortillaro of Geotecnica Veneta for the support on providing the gravel samples from different locations.

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