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Influence of Different Moisture and Load Conditions on Heat Transfer within Soils in Very Shallow Geothermal Application: An Overview of ITER Project

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ABSTRACT

In the near future the shallow geothermal energy resource is becoming increasingly important as renewable energy resource for heating/cooling residential and tertiary buildings.

Therefore, it is worthy of interest a better comprehension of how the different soil typologies (i.e. sand, loamy sand...) affect and are affected by the heat transfer exchange with heat collectors, especially when horizontal ones (very shallow geothermal installations) are adopted.

In this study the preliminary results of ITER Project (http://iter-geo.eu/), funded by European Union, are shown. An overview of physical-thermal properties variations under different moisture and load conditions for different mixtures of natural material is presented, based on laboratory and field test data.

1. INTRODUCTION

Since heating and cooling demands constitute almost 50% of the final energy demand in Europe, the development of geothermal energy systems and especially shallow geothermal solutions, reveals a huge potential in providing thermal energy for residential and tertiary buildings, thanks also to its local availability, manageability and flexibility (Urchueguía et al. 2013).

The development of shallow geothermal energy applications is a multidimensional process undergoing rapid improvement (Nagy and Körmendi 2012). There are still several challenges in the successful exploitation and in the profitable use of the earth's heat, as a better knowledge of the thermal properties of the ground, the efficient implementation of thermal energy transfers technologies and the environmental impacts in the short and long term (Angelino and Sanner 2013).

The applications of an energy efficient and environmentally friendly technology such as ground source heat pumps systems (GSHPs) for conditioning of residential, industrial or commercial buildings, are a long established practice and have been growing rapidly worldwide since the beginning of the 21st century (Quick et al 2013; EGEC 2015).

Two main categories of GSHPs are commonly adopted, the so-called open-loop or closed-loop systems. The former foresees the employment of groundwater as heat carrier fluid, brought directly to the heat pump and in direct contact with the surrounding environment; the latter, instead, uses water or a mix of water and antifreeze as heat carrier medium, circulating inside heat exchangers and in this way physically separated from the rock/soil and groundwater (Omer 2008; Banks 2012). Closed loop systems are becoming increasingly popular due to their ability to be installed virtually anywhere, to be used in heating and cooling mode and to reduce in a tangible way the energy costs related to building conditioning (Rybach and Sanner 2000; Busby et al 2009).

Among these systems, the most widespread are the vertical and horizontal ground heat exchangers. The former, preferred when the installation area is limited, consists of vertical oriented heat exchangers. Usually, in Europe, the vertical systems are (i) bored into the ground until at a depth of 100-150 m taking into consideration the national regulations related to this sector, (ii) thermally connected with the subsoil through grouting and (iii) characterized by high installation costs due to drilling operation. The latter, formed by horizontal loop systems located slightly below the earth's surface, requires the availability of ample ground area to dig trenches in order to host the system. The costs related to trenching activities are lower than those of well-drilling (Self et al 2013), but the thermal efficiency of horizontal heat exchangers suffers the ground temperature variation due to weather conditions (solar radiation, rain, water table presence). To ensure a good thermal exchange with the subsoil, the horizontal loops can assume different lengths and configurations (linear, helical, spiral) according to local characteristics and building conditioning requirements (Self et al 2013; Wu et al 2010). Recent works concluded that the helical heat exchangers, known as helix system, provide the best thermal performance compared to common horizontal loop systems, even if they need larger trenches and more tube length (Congedo et al 2012). Moreover, they are also a valid alternative to vertical systems installed at shallow depths (up to 25 m) (Zarrella et al 2013).

In addition, the performance of very shallow geothermal systems, as horizontal collector systems or special forms (i.e. heat baskets), interesting the first 2 m of depth from ground level, is strongly correlated to the kind of sediment locally available. The thermal behavior of soils depends on several factors, as the grain size, the water content, the mineralogical content, the ground temperature, the organic matter, the texture (Farouki 1981; Saxton et al 2006; Hiraiwa et al 2000; Gonzalez et al 2012; Nikolaev et al 2013). As shown by the recently ended ThermoMap EU Project (http://www.thermomap-project.eu/), an improvement of heat conductivity transfer is expected when the soil water content is increased (Bertermann et al 2014; Bertermann et al 2015). Moreover, a small addition of a natural additive (i.e. clay) to a coarse soil (i.e. sand) leads to an increase of its thermal conductivity (Farouki 1981; Smits et al 2010; Nikolaev et al 2013).

Taking into consideration these premises, one of the main aim of ITER Project (Improving Thermal Efficiency of horizontal ground heat exchangers, http://iter-geo.eu/), funded by European Union, is to consider the interactions between soil, horizontal heat exchangers and the surrounding environment. The preliminary results of the project, based on laboratory and field test data, are here shown. At first, the test site in Eltersdorf, near Erlangen (Germany), is presented. Here 5 helix, installed in a horizontal way instead of the traditional vertical option, have been located in five different trenches at a depth of 0.6 m below the ground level. Each sector was filled with a different mixture, ranging from natural material till commercial products and monthly monitoring of the main thermal parameters has been performed. Then, the laboratory activity focuses on measuring the physical-thermal properties of the selected mixtures, under different water content percentages and different consolidation degree. Finally, test field and laboratory data have been compared, in order to identify the factors that most influence the horizontal collectors under working conditions.

2. ITER PROJECT TEST SITE

The ITER project test site is located in Eltersdorf, about 10 km south-west from the city of Erlangen (Bavaria, Germany) (Fig.1a-b). Hosted on the property of REHAU AG & Co company, partner of the project, it consists of a trench 6.0 m wide, 5.0 m long and 1.1 m depth, divided in five sectors of the same size (1.2 x 5.0 x 1.1 m) (Fig.2c).

Figure 1: ITER Project test site location in Eltersdorf, Bavaria, Germany (a) and in the REHAU AG & Co facilities (b) [modified by Bayern Atlas]. Installation of 5 helix collectors in different sectors filled in with different soil mixtures and thermally isolated with XPD panels (c):

In each sector a surface collector system (helix probe, 3 m long, 0.4 m wide) is installed between 0.6 and 1 m depth below the ground level, equidistant from the boundaries. In order to thermally isolate every trench from the adjacent one and the surrounding ground, the outer and intermediate walls are made of XPS (extruded polystyrene, 2 cm thick) panels, characterized by very low thermal conductivity value (λ = 0.035 Wm^{-1}K^{-1}) (Fig.2a-b). Then the trenches are filled in with five soil mixtures as backfilling material, tested also in laboratory (Fig.2c):

1. fine sand 0-1 mm (*fs*);
2. fine sand 0-1 mm with 15% bentonite (*fs15B*);
3. sand 0-5 mm (*s*);
4. sand 0-5 mm + 15% bentonite (*s15B*);
5. sandy clay (*SC*);

The fine sand (*fs*) and the sand (*s*) selected for the test field are both sieved materials commonly used in constructions, provided with a well-defined grain size, ranging between 0-1 mm and 0-5 mm respectively. The *fs* is a grey white fine sand, while *s* is a reddish coarser sand, whose mineralogical phases consist mainly of quartz and feldspar. These pure materials are mixed with bentonite, amounting to 15% of the total weight, in order to obtain two soil mixtures whose physical-thermal behaviors in time is expected to differ from the original components. The bentonite (*B*) used in this project comes from Denmark and is made of several clay materials, where montmorillonite is dominant (> 60%). Finally, the sandy clay (*SC*), representative of a natural soil, shows a very high content of silicon oxide and clay minerals (i.e. illite, smectite).

Concerning the hydraulic system, the five helix are coupled as Tichelmann, each showing the same flow over 24 hours, and are connected to an absorber, able to stress the working condition. The measurement system allows to record every 15 minutes in a data logger, by means of devoted sensors, values related to the ground temperature inside and outside each helix (6 sensors), the undisturbed ground and surface temperature (2 sensors), the fluid temperature running in the collectors (4 sensors), the surface temperature of the absorber (2 sensors), the speed flow registered between the helix and the absorber (2 sensors), the volumetric water content at 20 and 60 cm depth (6 sensors). Moreover, a meteorological station provides climatic data acquisition related to light intensity (Lux), rainfall (mm/min), wind speed (m/s), wind direction (Grad), relative humidity (%). However, the analysis of the monitoring data is beyond the scope of this work, focused instead on determining the physical-thermal property variations of five soil mixtures according to soil moisture and load changes, both in laboratory and in the field test.

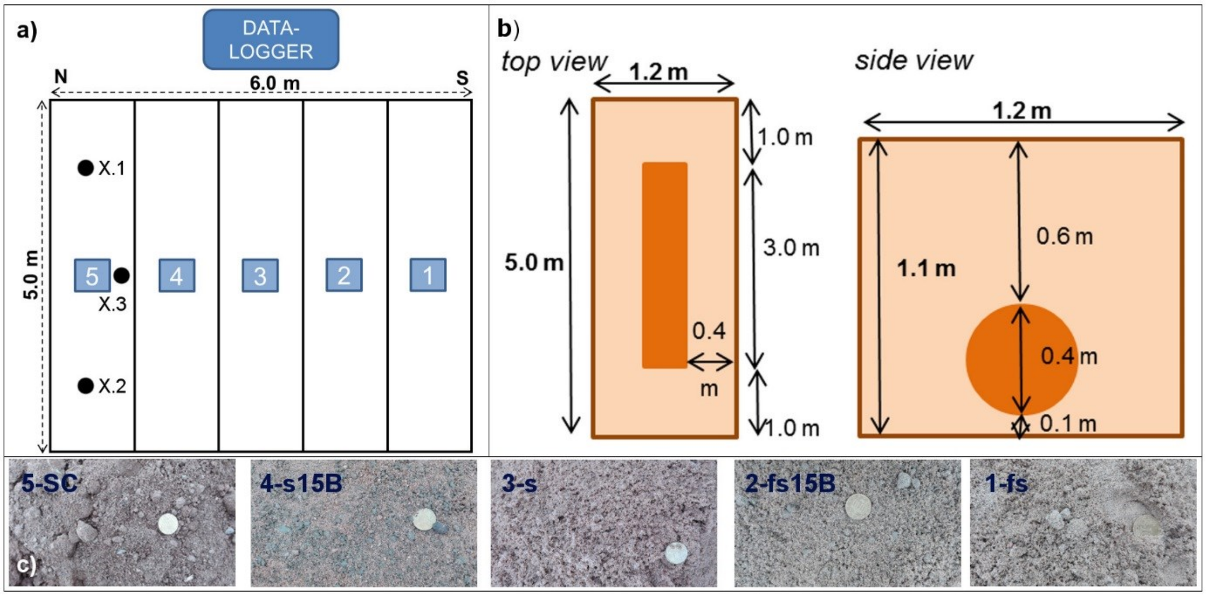

Figure 2: Overview of the ITER test site subdivision (a), installation schemes (top view and side view) of the helix inside each sector (b), and soil mixtures (c), used as backfilling material in each trench (SC = sandy clay; s15B = sand 0-5 mm + 15% bentonite; s = sand 0-5 mm; fs15B = fine sand 0-1 mm + 15% bentonite; fs = fine sand 0-1 mm).

3. METHODOLOGY

The physical-thermal properties of the sediments selected in the test field have been analyzed both in laboratory and directly in situ, in order to clarify their behavior respectively in a controlled environment or in unsteady conditions, affected by external factors (Di Sipio and Bertermann 2016). The main parameters determined are:

- *grain size* by sieving the sand fraction (<63 µm) of each mixture according to DIN 18123 and then using for the remaining fine particles the Sedigraph III Plus 5125 (Syvitski 2007). The Sedigraph measures the grain size distribution of the sample by means of X-ray radiation based on the sedimentation theory (Stokes's law) and the adsorption of X-rays (Beer-Lambert law).
- *thermal conductivity* by thermal properties analyzer (KD2Pro apparatus, Decagon Devices, Inc.). The device consists of a handheld controller and a single needle sensor probe (TR-1, 2.4 mm diameter, 10 cm long needle) operating according to the transient line source method (ASTM D5334-08), (Naylor et al 2015);
- *moisture content and bulk electrical conductivity* (measured simultaneously) by time domain reflectometry (TDR) device (TRIME IMKO GmBH). The device allows the determination of the soil moisture content, empirically related to the apparent dielectric constant (k_a) of the soil (Susha Lekshmi et al 2014);
- *bulk density* on duly collected sample (for every moisture content step and each load) according to the DIN 52102;
- *volumetric water content* on duly collected sample (for every moisture content step and each load) according to the DIN 18121;

At first, in laboratory, each mixture (about 60 kg) is naturally dried in a ventilated room at standard temperature and pressure condition. Once dried, the material is collected and subjected to parameter acquisition. During each phase, measurements of bulk density and volumetric water content are performed together with acquisition of moisture content, bulk electrical resistivity and thermal properties values. The entire measurement procedure is repeated for each mixture under different water content and incremental load steps (+0, +1, +3, +5 tons). In fact, fresh water is added gradually to the anhydrous soil until its field capacity is overcome, while it goes from unconsolidated till consolidated condition. In this way a complete set of data is obtained, available to be compared with the values acquired in situ.

Then, at the ITER Project test site in Eltersdorf, measurements of thermal conductivity and moisture content are collected monthly since November 2015. Given that the needle probe of both devices devoted to these measurements has a length of maximum 10 cm, the acquired data relate solely to the surface material, more affected by climatic fluctuations. Three measurement point have been selected for each sector at a distance of 1.0 (X.1), 2.5 (X.3) and 4 m (X.2) from the eastern boundary of the test field (Fig.2a).

However, occasionally, so as not to rework too much the sediments, samples are collected for determining later in laboratory the bulk density and volumetric water content of the soils, in order to validate the measurements and compare them with the laboratory results. The samples are collected both on surface and a depth of 0.2 and 0.4 cm from the ground level. In the latter case, data acquisition by IMKO and KD2Pro is also foreseen, in order to understand the parameter variation with depth.

4. RESULT AND DISCUSSION

2.1 laboratory results

The grain size analysis provides a first classification of the soil composition. According to the USDA (United States Department of Agriculture) textural soil classification, the selected ITER mixtures are defined as sand (*fs*, *s* 0-5 mm, *s* 0-4 mm), loamy sand (*SC*), sandy loam (*fs15B, s15B*) and clay (*B*), as the clay content increases (USDA 1987). Anyway, all soil samples, except the pure bentonite used as additive, have a high sand content, ranging between 75-100%. It must be noticed that in laboratory sand 0-4 mm with prevalent quartz and feldspar mineralogical composition was used instead of sand 0-5 mm adopted in situ, due to its greater availability on the market. As shown by the grain size analysis, these two materials do not have any substantial textural differences, while their mineralogical phases are consistent, according to producer description, so their thermal behavior is assumed to be comparable for ITER research purposes (Fig.3a).

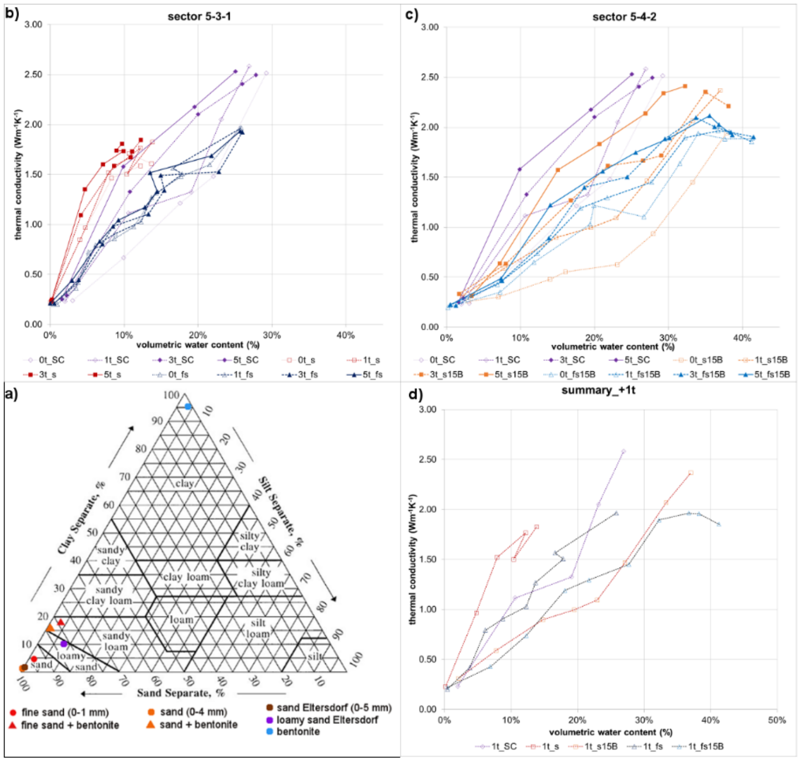

Figure 3: ITER laboratory results for the mixtures selected in the test field: USDA textural soil classification (a); relationship between thermal conductivity (λ) and volumetric water content (VWC) according to the incremental load step for sand and loamy sand (b) and for loamy sand and sandy loam (c) mixtures; trend of λ vs VWC values for all mixtures used in Eltersdorf for a load step of 1t (d).

Regarding the heat transfer capacity of the selected mixtures, the thermal conductivity (λ) trend increases as a function of the volumetric water content (VWC) and the pressure loads, as expected from literature (Fig.3b-c). In details, in completely anhydrous condition (VWC nearly 0%), the sediments show approximately a similar initial thermal conductivity value (ranging between 0.199 and 0.331 $Wm^{-1}K^{-1}$), typical of a dry soil whose pores are filled with air. Then, increasing the VWC amount, the heat transfer increases approximately linearly for each soil composition, showing a steep progression for the pure sands (*fs, s*), and a moderate trend for the loamy sand (*SC*) and sandy loam materials (*fs15B, s15B*). In the latter case, for example, for each incremental pressure step, increasing VWC, the bentonite mixtures diverge from the pure material (fine sand or sand) trend showing always a lower λ value. However, the gap between pure material and bentonite compounds is reduced at +5t step. As a matter of fact, increasing pressure on the soil, the heat transfer capacity of the mixtures comes close (Fig.3b-c).

Due to the prevalent quartz mineralogical composition, the pure sand (*s*) shows the better heat transfer performance in laboratory, followed, in descending order, by sandy clay (*SC*), pure fine sand (*fs*), sand with bentonite (*s15B*) and fine sand with bentonite (*fs15B*), The loamy sand behavior lies between that of a sand and a fine sand at the highest consolidation rate, and between the fine sand and the sandy loam (*fs15B, s15B*) for a pressure step equal to 0 or 1 tons, where 1ton is considered representative of the consolidation at approximately 1 m depth (Fig.3d).

However, despite the bentonite mixtures have the lowest λ values than the other mixtures in the same load condition, they show greater VWC contents (> 20%), thanks to a significant presence of clay minerals (up to 20%). Therefore, they can reach thermal conductivity values over 2 $Wm^{-1}K^{-1}$, overcoming the possible maximum value detected for the sand.

These results are representative of tests performed in laboratory, under controlled and reproducible conditions. When dealing with in situ test site, the meteorological and environmental conditions can influence the volumetric water content distribution on surface and in depth, affecting in this way the heat transfer capacity of the soils.

2.2 Field test results

Monthly measurements of thermal conductivity and moisture content have been collected since November 2015 at the test site in Eltersdorf. For each sector under investigation, 3 series of data have been collected by KD2Pro and IMKO. However, in the last winter season, from November 2016 till February 2017, the presence of frozen soil related to prolonged period of air temperatures below 0°C prevented the execution of reliable λ measurements, while in September 2016 the data have not been collected, due to the non-availability of the devices.

In situ, the mixtures specially created for the project (*fs15B, s15B*) reveal on surface (first 10 cm depth) a better performance than the corresponding pure material (*fs, s*), while the loamy sand (*SC*) shows a better heat transfer capacity over time (Fig.4a). Three different trends for thermal conductivity values can be recognized: (i) the lowest belongs to the pure sands ($1.0 < \lambda_{average} < 1.1$ $Wm^{-1}K^{-1}$); (ii) the highest to loamy sand ($\lambda_{average} > 2.0$ $Wm^{-1}K^{-1}$); (iii) the medium to bentonite mixture ($1.2 < \lambda_{average} < 1.3$ $Wm^{-1}K^{-1}$). The difference in behavior between pure and mixed materials compared to the lab results is connected to the moisture content (MC) (Fig.4b). Also in this case three main patterns are shown: (i) the first for the pure sands, characterized by the lowest values ($MC_{average} \approx 3.5$ %); (ii) the second for the loamy sand, with intermediate values ($MC_{average} \approx 10\%$); (iii) the third for the sandy loam with highest values ($MC_{average} \approx 15\%$). In fact, a remarkable improvement in the ability to retain water in the pores when bentonite is added to the pure material is observed (Fig.4a-b). Instead, the sandy clay material shows an intermediate trend for moisture content. However, this condition, combined with the original mineralogical composition of the *SC* sediment, results in the best thermal performance registered on field.

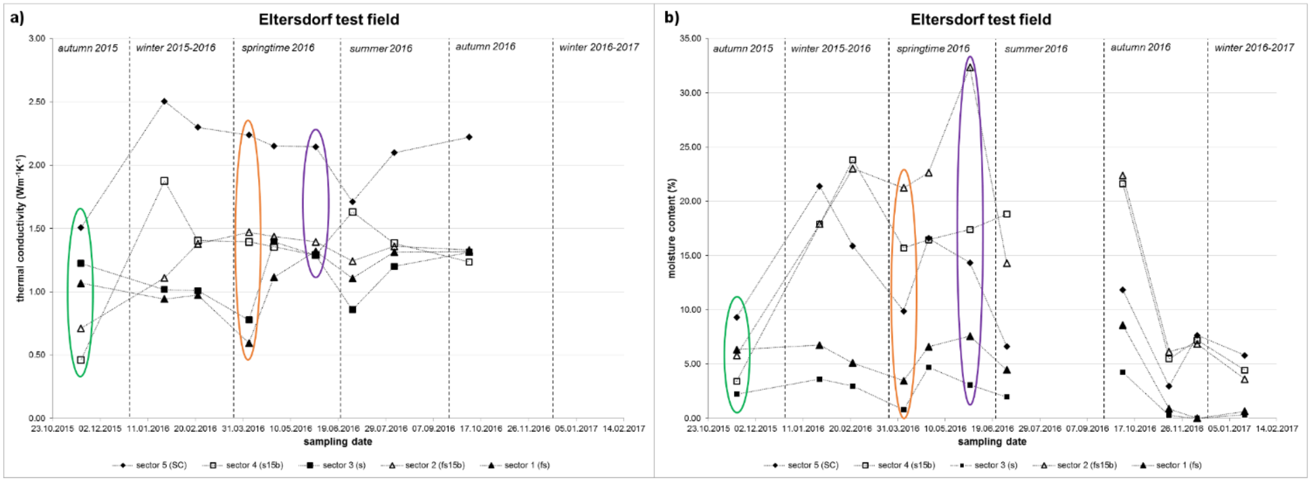

Figure 4: ITER test field results: variation of thermal conductivity (a) and moisture content (b) over time for the five mixtures selected for the Eltersdorf case study.

Under the same climatic conditions, the presence of water greatly contributes to a better heat exchange within the sediments. In detail, this can be explained taking into consideration three different sampling periods. In autumn 2015, the soil mixtures just put in the trenches have not yet undergone the natural compaction due to the weight of the unsaturated sediment. Then the contribution to the heat transfer can be ascribed mainly to the mineralogical composition, the presence of air in the voids and the texture of the material so, as expected from the laboratory results, the lowest λ values belong to the sandy loam materials. During the beginning of 2016 springtime (April 2016), the sampling was performed after a prolonged sunny period, able to reduce the moisture content of the sands below 5% while the same materials coupled with bentonite reveals a MC amount over 15%. As a consequence, the λ values for *fs15b* and *s15B* overcome those registered for *fs* and *s*. Instead, at the end of springtime 2016 (May 2016), after a rainy period, the MC content slightly increase in all the soil bodies. This factor has a negligible influence on the heat transfer capacity of the loamy sand and bentonite compounds, while it determines a steep increase of λ both for the fine sand and the sand material, in agreement with the laboratory results.

In order to verify the variation of physical thermal parameters with depth, some samples and measurements have been carried out from time to time in small trenches, dug in each sector until 40 cm depth from the ground level at a distance of 1.0 -2.5 - 4.0 m from the eastern boundary. Here the results obtained during the July 2016 sampling campaign are presented. Measurement of thermal conductivity and moisture content have been performed on surface, at 20 cm and 40 cm depth from the ground level.

At first, a comparison between MC data measured in the field by the time domain reflectometry (TDR) device and the real VWC determined in laboratory according to DIN 18121 on duly collected sample is shown (Table 1). As we can see, the two methods are different and return, as expected, a different absolute value. However, they are comparable in detecting the variations of the water content so the TDR can be used in a reliable way to observe the moisture content trend over time and depth.

	moisture content (%)	**volumetric water content (%)**
sector 5	7.90	8.28
sector 4	4.84	9.86
sector 3	3.51	3.95
sector 2	24.09	28.85
sector 1	6.91	6.55

Table 1: Comparison between MC data measured in the field by the time domain reflectometry (TDR) device and the real VWC determined in laboratory according to DIN 18121 on duly collected sample

Taking into consideration the moisture content and the thermal conductivity profiles for each sector (Fig.5), it is possible to notice:

- on surface (0 cm), the moisture content of the bentonite compounds is always higher than that of the related sand (Fig.5a-c), leading to higher (or similar) λ values in the sandy loam soils than (and) in the sand ones (Fig.5b-d);
- the sand bodies (*s, fs*) have little variation of MC with depth and, consequently, their thermal conductivity vary slightly from top to bottom;
- the sandy loam mixtures (*s15B, fs15B*) have more pronounced variation with depth, both for MC and λ values. Given that these changes have a different pattern moving from the eastern to the western border of each sector, a non-homogeneous distribution of the material in depth and length and a different consolidation degree due to the sectors' filling works must be considered. In detail, in sector 4 the bentonite mixed to the sand has created a top layer enriched in bentonite (about first 5 cm depth) that seems able to delay the infiltration of water from the surface. Therefore, the λ values rapidly decrease with depth. Sector 2 shows a similar distribution of bentonite near surface, and the λ values still decrease with depth, but they are also near to the *fs* ones due to a finer grain size.
- in the loamy sand material (*SC*) in every profile the MC changes are quite constant from top to 40 cm depth, while the thermal conductivity from one hand decreases with depth reaching a minimum at 20 cm below the ground surface, from the other shows the best heat transfer performance.

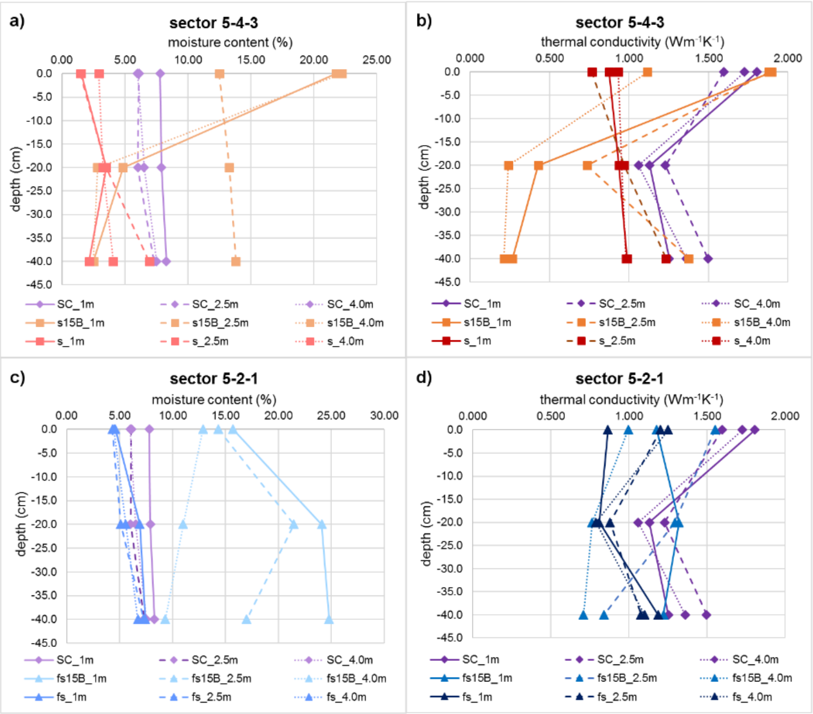

Figure 5: Variation of moisture content (a-c) and thermal conductivity (b-d) with depth measured at 1.0-2.5-4.0 m from the eastern boundary in every sector of Eltersdorf test site.

5. CONCLUSION

The preliminary outcomes of ITER Project, at the forefront of very shallow geothermal research, are encouraging.

In laboratory, under controlled and reproducible conditions, the bentonite mixtures specially created for the project shows a reduced ability to transfer heat compared with pure sand materials, but they can clearly carry a greater amount of water. This ability is essential to properly understand what happens in a real case study.

In fact, in the ITER Project test site in Eltersdorf, the best heat transfer performance over time, on surface and in depth (till 40 cm depth) belongs to the loamy sand material. In this sediment, the clayey component and the textural features of the material play a fundamental role in characterizing and preserving the thermal properties.

In addition, the bentonite mixtures specially created for the project reveal a better performance than the pure sands only, especially on surface. At first this seems not coherent with the lab outcomes, but focusing on the remarkable improvement in the ability to retain water when bentonite is added to the pure material, it is easy to understand how, in the same climatic conditions, this factor greatly contributes to improve the heat transfer within the sediments. However, the thermal conductivity variations with depth are also affected by the technical solutions adopted to fill in the trenches, that may have created a non-homogeneous mixing of the compound and different degree of consolidation in the soil bodies.

To clarify these aspects and strengthen the comprehension of how the different soil typologies affect and are affected by the heat transfer exchange with heat collectors, further development of the research is required. It is worthy of interest from one hand continuously monitor the moisture variations in the soil, close to the surface and at the top of the helix; on the other compare the performance of the 5 helix already installed. In this regard, the monitoring system is ready and in operation and in the coming months the data will be processed.

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REFERENCES

Angelino, L., and Sanner, B.: A Strategic Research and Innovation Agenda for Renewable Heating and Cooling: Key Findings. *Proceedings,* European Geothermal Congress 2013 Pisa, Italy (2013), EGC-MA-05: 1-6.

Banks, D.: An Introduction to Thermogeology: Ground Source Heating and Cooling, (2012), John Wiley & Sons, Ltd.

Bertermann, D., Klug, H., Morper-Busch, L., and Bialas, C.: Modelling vSGPs (very shallow geothermal potentials) in selected CSAs (case study areas), *Energy*, **71**, (2014), 226-244.

Bertermann, D., Klug, H., and Morper-Busch, L.: A pan-European planning basis for estimating the very shallow geothermal energy potentials, *Renewable Energy*, **75**, (2015), 335-347.

Busby, J., Lewis, M., Reeves, H., and Lawley, R.: Initial geological considerations before installing ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology*, **42(3)**, (2009), 295-306.

Congedo, P.M., Colangelo, G., and Starace, G.: CFD simulations of horizontal ground heat exchangers: a comparison among different configurations, *Applied Thermal Engineering,* 33, (2012), 24-32.

DIN 18121-1: Soil, Investigation and Testing: Water Content Part 1. Determination by Drying in Oven, *German Standard DIN*, Berlin (Deutsches Institut für Normung) (1998).

DIN 18123: Soil, Investigation and Testing: Determination of grain size distribution, *German Standard DIN*, Berlin (Deutsches Institut für Normung) (2011).

DIN 52102-02: Test methods for aggregates - Determination of dry bulk density by the cylinder method and calculation of the ratio of density, *German Standard DIN*, Berlin (Deutsches Institut für Normung) (2006).

Di Sipio, E., Bertermann, D.: Improving Thermal Efficiency of horizontal ground heat exchangers, *Proceedings*, EGC 2016 - European Geothermal Congress Proceedings, Strasbourg, France (2016).

EGEC: EGEC Geothermal Market Report 2015, (2015), EGEC Brussels.

Farouki, O.T.: Thermal properties of soils - Cold regions research and engineering lab, Hanover NH, (1981), No.CRREL-MONO-81-1.

Gonzalez, R. G., Verhoef, A., Vidale, P. L., Main, B., Gan, G., and Wu, Y.: Interactions between the physical soil environment and a horizontal ground coupled heat pump, for a domestic site in the UK, *Renewable energy*, **44**, (2012) 141-153.

Hiraiwa, Y., and Kasubuchi, T.: Temperature dependence of thermal conductivity of soil over a wide range of temperature (5–75 °C), *European Journal of Soil Science*, **51.2**, (2000), 211-218.

Nagy, K., and Körmendi, K.: Use of renewable energy sources in light of the “New Energy Strategy for Europe 2011–2020”, *Applied Energy,* **96**, (2012), 93-399.

Naylor, S., Ellett, K. M., Gustin, A. R.: Spatiotemporal variability of ground thermal properties in glacial sediments and implications for horizontal ground heat exchanger design, *Renewable Energy*, **81**, (2015), 21-30.

Nikolaev, I. V., Leong, W. H., and Rosen, M. A.: Experimental investigation of soil thermal conductivity over a wide temperature range, *International Journal of Thermophysics*, **34(6)**, (2013), 1110-1129.

Omer, A. M.: Ground-source heat pumps systems and applications. *Renewable Sustainable Energy Review*, **12 (2)**, (2008), 344 – 371.

Quick, H., Michael, J., Arslan, U., and Huber, H.: Geothermal application in low-enthalpy regions. *Renewable Energy,* **49**, (2013), 133-136.

Rybach, L., and Sanner, B.: Ground-source heat pump systems; the European experience. *Geo-Heat Center Bulletin*, **21**, (2000), 16-26.

Saxton, K. E., and Rawls, W. J.: Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil science society of America Journal,* **70(5)**, (2006), 1569-1578.

Self, S.J., Reddy, B.V., and Rose, M.A.: Geothermal heat pump systems: Status review and comparison with other heating options. *Applied Energy,* **101**, (2013), 341-348.

Smits, K. M., Sakaki, T., Limsuwat, A., and Illangasekare, T. H.: Thermal conductivity of sands under varying moisture and porosity in drainage–wetting cycles, *Vadose Zone Journal*, **9(1)**, (2010), 172-180.

Susha Lekshmi, S.U., Singh, D.N., Baghini, M.S.: A critical review of soil moisture measurement, *Measurement*, **54**, (2014), 92-105.

Syvitski, J. P.: Principles, methods and application of particle size analysis, Cambridge University Press, (2007).

Urchueguía, J.F., Alakangas, E., Berre, I., Cabeza, L.F., Grammelis, P., Haslinger, W., Hellmer, R., Mugnier, D., Papillon, P., Stryi-Hipp, G., and van Helden, W.: Strategic Research and Innovation Agenda for Renewable Heating & Cooling. *RHC-Platform* (2013), 1-116.

USDA United States Department of Agriculture: Soil Mechanics Level 1 - Module 3, USDA textural soil classification, (1987), Study Guide, Soil Conservation Service USDA.

Wu, Y., Gan, G., Verhoef, A., Vidale, P.L., and Gonzalez, R.G.: Experimental measurement and numerical simulation of horizontal-coupled slinky ground source heat exchangers. *Applied Thermal Engineering,* **30(16)**, (2010), 2574-2583.

Zarrella, A., Capozza, A., and De Carli, M.: Analysis of short helical and double U-tube borehole heat exchangers: A simulation-based comparison. *Applied Thermal Engineering,* **112(0),** (2013), 358 - 370.

Web references

Bayerische Staatsregierung http://geoportal.bayern.de/geoportalbayern/ (last accessed 27.01.2017)

ITER Project website http://iter-geo.eu/ (last accessed 27.01.2017)