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An updated ground thermal properties database for GSHP applications

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ABSTRACT

When a new ground source heat exchanger field is planned, underground thermal properties input data are necessary for the correct sizing of the geo-exchange system. To support the design, the EU founded Cheap-GSHPs project developed a Decision Support System, that comprises a new database of thermal properties for both rocks and unconsolidated sediments. The thermal properties database has been developed by integrating and comparing data (1) provided by the most important international guidelines, (2) acquired from a wide literature review and (3) obtained from more than 400 direct measurements. The data are mainly thermal conductivity data, hence the convective contribution provided by groundwater flow to heat transfer is not included. This paper presents and analyses the collected database.

1. Introduction

Low enthalpy geothermal energy is one of the most common renewable energy sources for heating and cooling of buildings as a result of its ubiquitous potential. In a closed loop geothermal system, a series of borehole heat exchangers are inserted into the ground. These allow the transfer of heat between the ground and the building to take place through a heat carrier fluid flowing in the boreholes. In winter, the heat is extracted from the ground and transferred to the building, whilst, in summer, the heat is removed from the building and rejected to the ground. Unless passive heating/cooling is used, the heat pump manages the whole system by transferring the heat between the underground circuit by raising or decreasing the fluid temperature needed in the building heating and cooling circuit to satisfy the demand.

The design of a new closed loop Ground Source Heat Pump (GSHP) system, requires three relevant aspects to be taken into consideration, including: (1) climate and location of the building, (2) building characteristics, such as the building' use, size and insulation level, and (3) ground conditions, including the ground temperature profile. The first two elements determine the heating and cooling demand of the building while the evaluation of the thermal exchange potential of the local geological setting depends on the ground conditions, i.e. the stratigraphic succession and the hydrogeological conditions. The amount of heat exchanged and the energetic performance of the whole system are strongly affected by the heat exchange capacity of the ground surrounding the Borehole Heat Exchangers (BHE) (Sarbu and Sebarchievici, 2014). Another key factor is the balance between the heating and the cooling building demands: in case of an unbalanced demand, the thermal behavior of the ground affects more significantly the evolution in time of the overall energy performance.

Therefore, the determination of the ground thermal parameters is crucial both to designing the adequate total borehole length to be installed, the BHEs spacing and layout, i.e. single BHE length, numbers of BHEs and mutual position, that affect the installation costs in the short term and also to maintain suitable energetic performance of the GSHP system in the long term. The effects of an incorrect evaluation of the

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local thermal exchange capacity of the ground could lead to an incorrect design of the borefield, therefore affecting the installation, performance and the running costs of the GSHP system. For example, if the global value of the ground thermal conductivity is overestimated during the design, the calculated total length of the collector required to supply the requested heating and cooling demand of the building will be undersized. Consequently, the whole GSHP system will show a lower energy efficiency of the heat pump and a higher electrical energy consumption. Conversely, in case of an underestimation of the thermal exchange capacity, the requested borehole total length will be longer than necessary and the initial installation costs of the borefield will be higher, although the operating energy efficiency will be greater than the value set in design phase.

The "Cheap-GSHPs" (Cheap and efficient application of reliable Ground Source Heat exchangers and Pumps) European project (http://cheap-gshp.eu/) undertaken under the Horizon 2020 EU framework program for Research and Innovation, is aimed at reducing the overall engineering and installation costs of closed loop geothermal systems and at improving installation safety. This project involves 17 partners from nine European countries: Belgium, France, Germany, Greece, Ireland, Italy, Romania, Spain, and Switzerland; it started in June 2015 and ended in May 2019.

The Cheap-GSHPs project has developed a Decision Support System (DSS), among other outputs, in order to assist users and support the decision-making process of designers of new GSHP system and building owners. The DSS combines models and data in an attempt to support decision-making and preliminary design of new closed-loop ground source heat pump installations. This is a user-friendly web-based application that enables the end-users to identify the best Ground Source Heat Exchanger (GSHE) and heat pump based on the local underground, the building heating and cooling demands, the climatic conditions as well as the owners' criteria. The DSS is composed of several analytical linked to system parameter databases concerning the most important aspects of the new GSHP closed-loop systems design. These parameters include: (I) a comprehensive dataset of climate conditions and spatial undisturbed ground temperature in Europe (De Carli et al., 2018), (II) standard temporal profiles of heating and cooling requirements for several standardized building typologies (4 standardized residential buildings and 5 standardized non-residential building typologies of) that take into account several building thermal insulation levels (Carnieletto et al., 2019) and (III) a very shallow, pan-European geological map representing a lithological overview of the dominant parent material that can be used for a first evaluation of the level of hardness and the drilling conditions (Müller et al., 2018). In addition to these, in order to support the evaluation of the local thermal exchange potential, a thermal properties database of rocks and unconsolidated sediments has been developed for inclusion in the DSS. The database integrates published literature data, values from international best practice guidelines and new experimental data obtained from more than 400 direct measurements performed on rock samples and unconsolidated sediments collected by the project partners in several European countries. The values in the database can be used during the design phase of a new ground source heat pump system to directly provide the thermal parameter values of the identified deposits when the stratigraphy is available. In addition, the thermal properties database has been further developed during the EU project GEO4CIVHIC "Most Easy, Efficient and Low Cost Geothermal Systems for Retrofitting Civil and Historical Buildings", where the previous results are applied to the heating and cooling systems in the retrofitting of historical buildings.

2. Materials and methods

The most important thermal characteristics of the local underground to be taken into account when designing a new closed loop geothermal system are:

1.thermal conductivity, defined as the ability to transfer heat, usually expressed in W/m K;

2.heat capacity, defined as the ability to store heat. It is the ratio between the amount of heat to be transferred to a certain mass or volume in order to achieve a defined change in temperature, thus it is expressed in J/K; it depends on the material but also on the mass/volume and, therefore, the 'specific' heat capacity is usually used;

3.thermal diffusivity, that is the ratio of the first two, defined as the physical property governing the heat diffusion in transient conditions measuring the penetration of temperature changes into a material.

4. undisturbed ground temperature profile, that varies in the shallower layers as a function of the air temperature whilst, from about 10 m, is stable throughout the year and increases with depth based on the local geothermal heat flux.

In addition to these, the local groundwater flow in the aquifers can significantly affect the global capability of exchanging heat by adding a significant contribution of heat exchanged by convection, which is not accounted for in the thermal conductivity value.

In this paper, a literature review of thermal conductivity values is presented, combined with direct measurements data on rocks and sediments samples.

The thermal conductivity of soils and rocks can be determined by means of in-situ tests such as Thermal Response Tests (TRT) or by laboratory measurements performed on specimens collected from each layer of the geological sequence under investigation. The TRT takes into account the site-specific conditions such as the presence of several lithological layer, groundwater flow and 'scale effects', due to the large volume involved in the heat exchange during the test, that directly impact the effective thermal properties. The TRT usually provides an equivalent value of the local thermal exchange capacity of the ground heat exchanger in the entire local geological context, including the groundwater conditions (Gehlin, 2002). Conversely, laboratory measurements are conducted directly on samples of specific layers of the stratigraphic sequence, these do not allow the influence of groundwater flow to be evaluated. The laboratory measured values can be related to the generalised properties of the tested materials and can be integrated in a database by collecting a large amount of experimental values.

2.1. Thermal conductivity of rocks

The thermal conductivity coefficient of a material represents its ability to transfer thermal energy (heat) by conduction. As it represents the amount of heat (W or J/s) flowing through a unit surface area (m^2) for a unit of temperature difference (gradient, K m^{-1}) the thermal conductivity λ is expressed as $Wm^{-1}K^{-1}$.

Similarly to other properties, thermal conductivity is characterized by a large range of values within the same rock type. Table 1 lists the references reporting data for each type of rock. Fig. 1 presents thermal conductivity values presented in literature for the most common rock types.

Fig. 1 highlights the variability in thermal conductivity for single lithologies. This is a collection of data reported by different authors for the same lithology. They have been obtained by means of different experimental devices and methodologies. In addition, they are reported in literature in different ways; sometimes the median only is reported, in other cases the maximum and the minimum values are indicated. The variability of the reported values does not allow for a correct statistical analysis to be performed and only the range of variability can be represented.

This spread of values is a result of several governing factors that affect thermal conductivity including temperature, porosity, degree of saturation, pore fluid, dominant mineral phase, texture and anisotropy (Schön, 2011). Clauser and Huenges (1995) defined two ternary diagrams highlighting the effect of the mineralogical composition and the presence of air and water in the pore space for different rock types (Fig. 2). For volcanic and sedimentary rocks the third "mineral" phase is

Table 1
References reporting thermal conductivity data for each lithotype. In the table, the references providing recommended values of thermal conductivity are highlighted by means of the *symbol.

Rocks	References
SEDIMENTARY	
conglomerate	VDI, 2010*; Gangyan, 2005; Eppelbaum et al., 2014*; Reiter and Tovar, 1982; Bloomer, 1981
sandstone	VDI, 2010*; Chiasson et al., 2000; Gangyan, 2005; Lee and Deming, 1998; Lienhard and Lienhard, 2011*; Moiseyenko et al., 1970; ASHRAE, 2011; Özkahraman et al., 2004; Pasquale et al., 2011; Robertson, 1988; Yaşar et al., 2008; Banks, 2008; Reiter and Tovar, 1982; Midttømme et al., 1998; Bloomer, 1981; Park et al., 2004
clay-mudstone	VDI, 2010*; Chiasson et al., 2000; Gangyan, 2005; Moiseyenko et al., 1970; ASHRAE, 2011; Eppelbaum et al., 2014*; Sharma, 2002*; Pasquale et al., 2011; Yaşar et al., 2008; Banks, 2008; Reiter and Tovar, 1982; Bloomer, 1981; Park et al., 2004
limestone	VDI, 2010*; Chiasson et al., 2000; Gangyan, 2005; Lee and Deming, 1998; Lienhard and Lienhard, 2011*; Moiseyenko et al., 1970; ASHRAE, 2011; Eppelbaum et al., 2014*; Sharma, 2002*; Özkahraman et al., 2004; Pasquale et al., 2011; Yaşar et al., 2008; Banks, 2008; Reiter and Tovar, 1982; Park et al., 2004
dolomite	VDI, 2010*; Gangyan, 2005; Lee and Deming, 1998; Pasquale et al., 2011; Robertson, 1988; Yaşar et al., 2008; Reiter and Tovar, 1982; Park et al., 2004
marlstone	VDI, 2010*; Eppelbaum et al., 2014*
gypsum	VDI, 2010*; Gangyan, 2005; Pasquale et al., 2011
anhydrite	VDI, 2010*; Sharma, 2002*; Pasquale et al., 2011; Robertson, 1988; Reiter and Tovar, 1982
IGNEOUS	
granite	Schön, 2011; VDI, 2010*; Lee and Deming, 1998; Lienhard and Lienhard, 2011*; Moiseyenko et al., 1970; ASHRAE, 2011; Eppelbaum et al., 2014*; Sharma, 2002*; Özkahraman et al., 2004; Banks, 2008
diorite	Schön, 2011; VDI, 2010*; Gangyan, 2005; Lee and Deming, 1998; Moiseyenko et al., 1970; Eppelbaum et al., 2014*; Sharma, 2002*
syenite	Schön, 2011; VDI, 2010*; Robertson, 1988
gabbro	Schön, 2011; VDI, 2010*; Gangyan, 2005; Lee and Deming, 1998; Moiseyenko et al., 1970; Eppelbaum et al., 2014*; Mottaghy et al., 2005; Sharma, 2002*; Robertson, 1988
rhyolite	VDI, 2010*; Moiseyenko et al., 1970; Robertson, 1988
dacite	VDI, 2010*; Pasquale et al., 2011
andesite	Schön, 2011; VDI, 2010*; Özkahraman et al., 2004; Yaşar et al., 2008
trachyte	VDI, 2010*; Eppelbaum et al., 2014*; Sharma, 2002*
basalt	Schön, 2011; VDI, 2010*; Moiseyenko et al., 1970; Eppelbaum et al., 2014*; Sharma, 2002*; Yaşar et al., 2008; Banks, 2008
tuff/tuffstone	VDI, 2010*; Moiseyenko et al., 1970
METAMORPHIC	
quartzite schist	Schön, 2011; VDI, 2010*; Gangyan, 2005; Lee and Deming, 1998; Eppelbaum et al., 2014*; Sharma, 2002*; Özkahraman et al., 2004; Robertson, 1988; Banks, 2008; Reiter and Tovar, 1982
micaschist	Schön, 2011; VDI, 2010*; Gangyan, 2005; Eppelbaum et al., 2014*; Robertson, 1988
gneiss	Schön, 2011; VDI, 2010*; Gangyan, 2005; Lee and Deming, 1998; Eppelbaum et al., 2014*; Mottaghy et al., 2005; Sharma, 2002*; Robertson, 1988; Banks, 2008
phyllite	Lee and Deming, 1998; Lienhard and Lienhard, 2011*; Eppelbaum et al., 2014*; Mottaghy et al., 2005; Sharma, 2002*; Robertson, 1988; Banks, 2008
amphibolite	Schön, 2011; VDI, 2010*; Gangyan, 2005; Lee and Deming, 1998; Mottaghy et al., 2005; Pasquale et al., 2011; Robertson, 1988
serpentinite	Gangyan, 2005; Osako et al., 2010*
marble	Schön, 2011; VDI, 2010*; Gangyan, 2005; Lee and Deming, 1998; Özkahraman et al., 2004; Robertson, 1988; Yaşar et al., 2008

air or water, due to the importance of porosity on the thermal conductivity (Clauser and Huenges, 1995). The position of a rock type label in the compositional triangle, indicates in a qualitative way its thermal conductivity. In sedimentary rocks, only pore-free sediments show a relative narrow range of values (i.e. Carbonate), related mainly to mineralogical composition variation, the presence of impurities, whilst the influence of porosity and pore fluid are of secondary importance. In all other cases, porosity has a great influence because of the distinct difference between conductivity of matrix materials (minerals) and pore-filling material. Air and water, when dry and wet samples are measured respectively, have lower conductivity than minerals so a great quantity of pores causes a decrease in thermal conductivity.

2.2. *Thermal conductivity of unconsolidated sediments*

The thermal conductivity of unconsolidated sediments depends on several factors such as water content, mineralogical composition, grain size distribution and gradation, organic content, soil density and overburden pressure, which often interact with each other affecting the thermal properties of the sediments (Tarnawski et al., 2009; Abu-Hamdeh, 2003).

The graphs in Fig. 3 summarize the measurements reported in scientific papers by several authors as an overview of the thermal conductivity values for sands and silts/clays.

The thermal properties data (Fig. 3) of the same category display quite a wide range of variation due to the difference in the physical-structural properties of the tested materials; the unconsolidated sediments present, a very high variability in terms of mineralogical composition and granulometric gradation even if classified as belonging to the same granulometric main class. Differences in measuring conditions reported in the literature including water content (dry/wet) or degree of consolidation (loose soils /slurry, normal-consolidated or over-consolidated clayey materials) are responsible for the main variations. Moreover, the thermal properties of a given sediment changes according to temperature (Nikolaev et al., 2013). The most significant change occurs in the case of freezing/thawing of the ground in the BHEs surroundings. This occurrs when the BHE system is undersized with respect to the building's heating demand, in case of very low undisturbed ground temperature or, when unbalanced operation of the heat pump towards heating leads to a progressive cooling of the ground temperature. In the case of freezing, the thermal conductivity of coarse soil may be considered to increase abruptly as the sediment freezes (Dalla Santa et al., 2019a), while in fine-grained soils the increase is more gradual (Farouki, 1981). In addition, freezing-thawing cycles in moist, cohesive sediments, affect their mechanical properties (Dalla Santa et al., 2016a, 2019b).

The data reported in literature are acquired by means of several devices based on different working principles including hot wire, plane probes, parallel plates, divided bar, Tempe cell etc. (Vieira et al., 2017). These can lead to quite different experimental values and because the experimental test may have been carried out at different temperature conditions.

Direct measurements of thermal properties of gravel samples, are quite challenging mainly due to technical issues related to very coarse sediment size, which impedes an appropriate physical contact between the tested material and the traditional thermal measuring sensors. Moreover, the variability of the mineralogical composition of such polygenic samples, requires that quite a large volume of geological

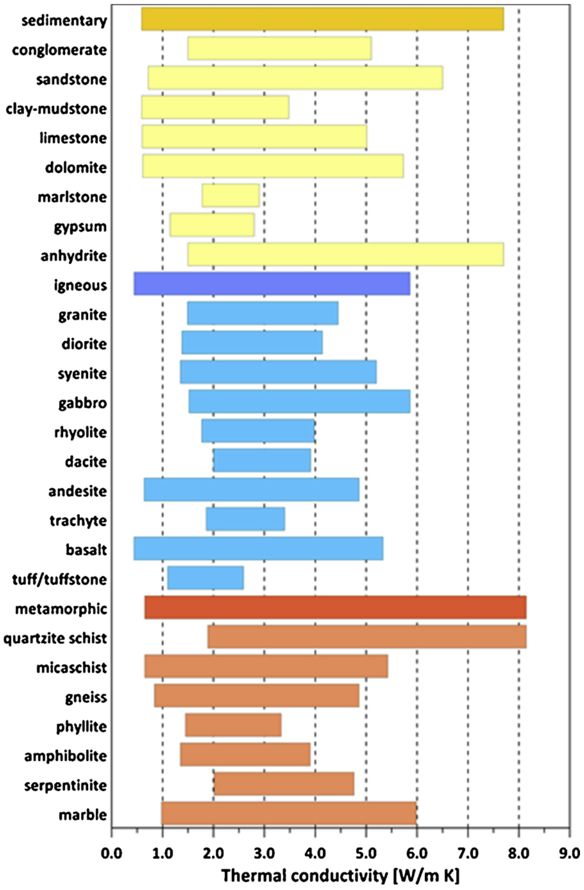


Fig. 1. Thermal conductivity variability for some rocks according to porosity and pore fluid.

material is investigated during the measurement procedure to obtain representative thermal property values. In the past, some researchers proposed original devices for measuring thermal conductivity of gravels (Jones, 1988; Koemle et al., 2010). B. W. Jones (1988) for the first time developed a probe method for measuring the thermal conductivity of gravels 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 $\mathrm{W m^{-1} K^{-1}}$ at 25 °C (dry conditions), increasing slightly with temperature. More recently, other authors (Koemle et al., 2010) concluded that gravel thermal conductivity is more strongly affected by the clasts mineralogical composition rather than by the dimensions of the clasts themselves based on the tests performed. These compared the thermal conductivity measured from gravel samples of similar angular shaped clasts and dimensions (quite homogeneous), but of different mineralogical compositions. The tests were repeated for three different granulometric classes on samples of calcareous (calcite 87%, dolomite 11%), granitic (quartz 22%, plagioclase 25%, orthoclase 22% and biotite 29%) and rhyolitic lava clasts. In addition, porosity was observed as having a significant influence on the measured values.

The relationship between the thermal conductivity values measured in the experimental tests of the main sample and the characteristics of the unconsolidated sediments (fine and coarse) such as granulometry, porosity, mineralogical composition and water content has yet to be clearly understood.

The high variability of the thermal conductivity values present in literature and in guidelines to predict the thermal exchange capacity of the ground layers around a borehole heat exchanger are shown in Table 2.

2.3. *The thermal properties testing devices used*

The methods that are commonly adopted to measure thermal conductivity of samples of rocks or sediments can be divided into two principal categories, the steady-state (or stationary) and transient methods. The steady-state methods determine thermal properties by establishing a temperature difference across the sample that does not change with time, while transient methods monitor the time-dependent heat dissipation within a sample (Vieira et al., 2017). Transient methods are usually much faster than steady-state methods that require (i) a long time to reach the steady conditions, (ii) an apparatus able to guarantee a stable thermal condition to perform the measurement, (iii) an accurate control to create and maintain the stability of measurement conditions.

Within the framework of Cheap-GSHP Project, the thermal properties (thermal conductivity and thermal diffusivity) have been measured by using the following devices:

- for rock samples:

- the TCi Thermal Conductivity Analyzer (manufactured by C-Therm Technologies) at the Thermal Properties laboratory of National Research Council, Institute of Geosciences and Earth Resources, Padova (Italy);
- the Thermal Conductivity Scanning (TCS) apparatus at the laboratories of the GeoCentre of Northern Bavaria, Friedrich-Alexander-University (FAU) Erlangen-Nuremberg (Germany).

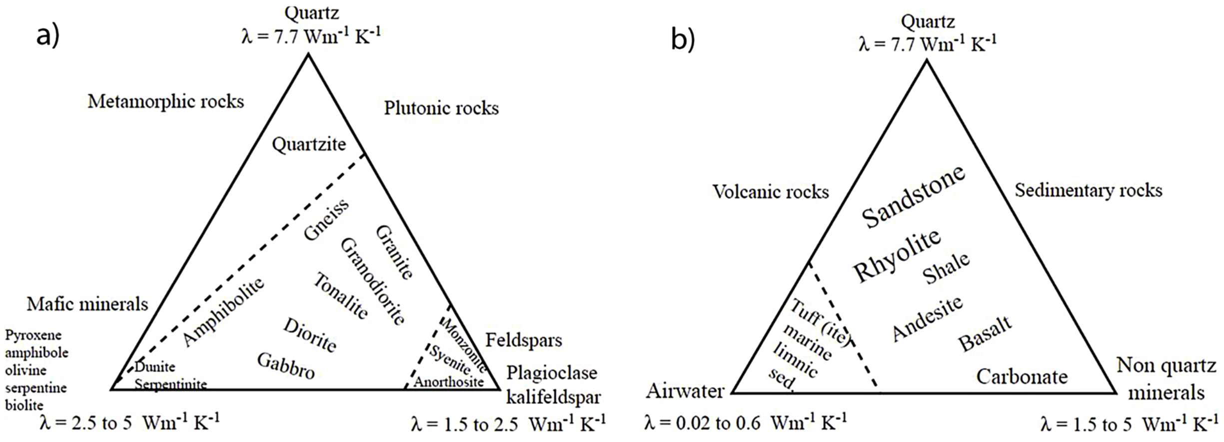
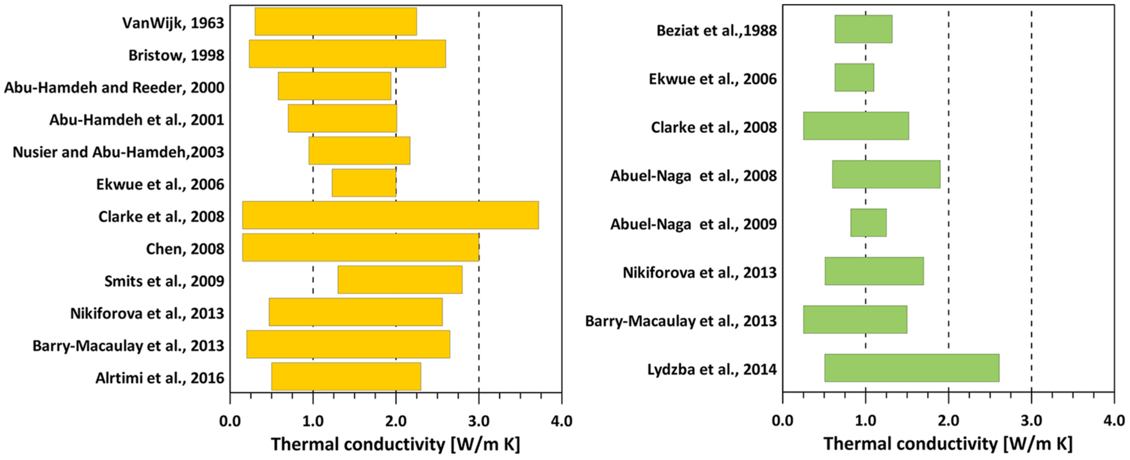


Fig. 2. Thermal conductivity of basic rock-forming minerals and compositional relationship with rocks. (a) Metamorphic and plutonic rocks, (b) volcanic and sedimentary rocks (from Clauser and Huenges, 1995).



(a) (b)

Fig. 3. Overview of the thermal conductivity values derived from literature for sands (a) and silts/clays (b) (Abuel-Naga et al., 2008; Abuel-Naga et al., 2009; Abu-Hamdeh et al., 2001; Abu-Hamdeh and Reeder, 2000; Alrtimi et al., 2016; Barry-Macaulay et al., 2013; Beziat et al., 1988; Bristow, 1998; Chen, 2008; Clarke et al., 2008; Ekwue et al., 2006; Lydzba et al., 2014; Nikiforova et al., 2013; Nusier and Abu-Hamdeh, 2003; Smits et al., 2009; Van Wijk, 1963).

Table 2
Thermal conductivity reference values extracted from literature (VDI 4640, 2010). The reported values do not take into account the convection contribution to the heat transfer that can be achieved in case the BHEs encounter flowing groundwater.

	Thermal Conductivity [W/m K]		
Sediment category	Min-value	Max-value	Recommended value
Gravel dry	0.4	0.9	0.4
Gravel water-saturated	1.6	2.5	1.8
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

- for unconsolidated sediment samples:

- ISOMET 2114 Thermal Properties Analyser, for experimental measures performed on the loose unconsolidated sediments at the University of Padova (Italy),
- the Thermal Conductivity Scanning (TCS) apparatus at the laboratories of the GeoCentre of Northern Bavaria, Friedrich-Alexander-University (FAU) Erlangen-Nuremberg (Germany), applied on the overconsolidated clay samples,
- a guarded hot plate Taurus Instruments TLP 800, that has been proper modified in order to measure the gravel samples.

Each of these devices is described below.

TCi Thermal Conductivity Analyzer

The TCi Thermal Conductivity Analyzer uses the Modified Transient Plane Source technique by using a one-sided, interfacial heat reflectance sensor that applies a momentary constant heat source to the sample in accordance with ASTM methods (ASTM D7984-16, 2016). The sensor used consists in a guard ring surrounding the primary sensor coil (diameter of 1.5 cm) in order to induce a one dimensional heat transfer into the sample.

This device was used only to measure rock samples.

Before each measuring session, the device is calibrated with proper reference samples provided by the manufacturer. These are tested for thermal conductivity measurement by external third-party certified labs. The measuring sensor is applied on the flat surface of the testing sample, after a polishing operation.

In addition to thermal conductivity, laboratory measurements of physical properties to better characterize each rock sample such as porosity and density were performed.

Each specimen was tested in fully dry and fully saturated conditions.

The thermal conductivity and thermal diffusivity were measured on two orthogonal faces of each specimen; on each face the sensor was applied at 5 different measurement points in order to test the homogeneity of the thermal properties and the measurement repeated 10 times in order to test the repeatability of the method used at each point.

The accuracy is reported in Table 3.

Table 3
Characteristics of all the devices used for the thermal properties measurements, as defined in the certificates provided by the producers. *Note that the accuracy here reported for Taurus Instrument TLP800 is the one provided by the producer, not for the modified device.

	Parameter	Measurement range	Accuracy	Used on
C-Therm tCi thermal conductivity analyser	Thermal Conductivity	0-100 $\mathrm{Wm^{-1}K^{-1}}$	5 %	*rocks*
	Volume heat capacity	$4*10^4$-$3*10^6$ $\mathrm{Jm^{-3}K^{-1}}$	5 %	
Thermal Conductivity Scanning	Thermal Conductivity	0.2-25 $\mathrm{Wm^{-1}K^{-1}}$	3 %	*rocks, consolidated clays*
ISOMET 2114 Thermal Properties Analyser	Thermal Conductivity	0.015-0.70 $\mathrm{Wm^{-1}K^{-1}}$ 0.70-6.0 $\mathrm{Wm^{-1}K^{-1}}$	5 % reading + 0.001 $\mathrm{Wm^{-1}K^{-1}}$ 10 % reading	*sands, silts, clays*
	Volume heat capacity	$4*10^4$-$3*10^6$ $\mathrm{Jm^{-3}K^{-1}}$	15 % reading + $1*10^3$ $\mathrm{Jm^{-3}K^{-1}}$	
	Temperature	−20 - +70 °C	± 1 °C	
Taurus Instruments TLP 800	Thermal Conductivity	0.005-2.0 $\mathrm{Wm^{-1}K^{-1}}$	2.5 % *	*gravel*

Table 4
The Table reports the categories of rocks and unconsolidated sediments on which the direct measurements have been performed. The formation, sampling location and in the second column, the number of available samples are reported. In brackets the number of samples is reported, when they belong to the same formation (location for the unconsolidated sediments).

Rock / sediment	Number of samples	Formation (sampling location)
Sedimentary rocks		
sandstone	18	Old Red Sandstone (Lyons Hill - Ireland), Werfen (Pressano - Italy), Hassberge Formation (Höchstadt an der Aisch, Bavaria, Germany) [16]
clay-mudstone	13	Boston Hill (Blanchardstown - Ireland), Waulsortion (Newbridge – Ireland), Steigerwald Formation (Höchstadt an der Aisch, Bavaria, Germany) [11]
limestone	11	Frido Unit (Amantea –Italy), Rosso Ammonitico Veronese (Pila - Italy), Crufty (Drogheda – Ireland), Ballysteen (Newbridge – Ireland), Scaglia Rossa (Sant'Anna d'Alfaedo - Italy), Rosso Ammonitico Veronese (Cerro Veronese - Italy), Marsala Calcarenite (San Vito Lo Capo – Italy), Lucan (Dublin - Ireland), Diemel Formation (Würzburg, Germany) [3]
dolomite	11	Torra Dolostone (Val di Non - Italy) [8], Contrin (Ville di Giovo, Italy), Werfen (Palù di Giovo - Italy) [2]
Igneous rocks		
granite	5	Leinster Granite (Blessington - Ireland), Leinster Granite (Co.Wicklow - Ireland), Villa Simius Granite (Cagliari –Italy), Granito di Baveno (Baveno - Italy), Granito Rosso (Omegna - Novara)
diorite	6	Granodiorite Stillo Unit (Soverato – Italy), Leinster Granite (Dublin - Ireland), Sostino Granodiorite (Caderzone Terme - Italy), Caderzone Leucogranodiorite (Pra Rodont - Italy), Doss de Sabion Granodiorite (Pra Rodont - Italy), Tonalite dell'Adamello (Adamello - Italy)
syenite	1	Monzoni Sienite (Monzoni - Italy)
gabbro	1	Ivrea Gabbro (Ivrea – Italy)
rhyolite	5	Athesian Volcanic Group (Albiano –Italy) [2], Monte Venda Rhyolite (Torreglia, Monte Rua - Italy) [3]
andesite	5	Triassic Andesite (Garés Agordino – Italy) [5]
trachyte	5	Mt. Venda Trachyte, Mt. Venda Formation (Montemerlo quarry, Rocca Pendice, Turri – Italy) [4]
basalt	5	San Giovanni Ilarione Basalt (Tregnago – Italy) [2], Mt. Venda Formation Basalt (Abano Terme - Italy), Ignimbrite Campana (Torre del Greco, Roccamonfina – Italy) [2]
Metamorphic rocks		
micaschist	4	Ms-Bt Scist Castagna Unit (Paola – Italy), Val Rendena Shist (Vigo Rendena, Pra Rodont - Italy) [3]
gneiss	1	Grt-Bt-Sil Gneiss Monte Gariglione Unit (Rende - Italy)
phyllite	6	Valsugana Quartz-Phyllite (Madrano di Pergine - Italy), Comelico Phyllite (Rivamonte Agordino, Sega Digon, Costalissoio - Italy) [5]
serpentinite	2	Diamante Unit, Terranova (Amantea – Italy), Gimigliano Unit (Rende – Italy)
Unconsolidated sediments		
gravel	8	(Torretta, Castelfranco, Treviso, Zevio, Perzacco, Padova, Brenta river - Italy), (Main river bed, Breitengüßbach, Northern Bavaria – Germany)
sand	18	(Tessera, Duino, Marene, Padova [6], Molinella [4], Brenta river – Italy), (Zagreb – Croatia) [3], (Athens – Greece)
silty sand	17	(Duino, Molinella [5], Padova [7] – Italy), (Zagabria – Croatia) [4]
silt	18	(Torretta, Padova [4], Molinella [9] – Italy), (Zagabria – Croatia) [4]
clay	20	(Campogalliano, Molinella [9], Padova[3] – Italy), (Athens – Greece), (Zagreb – Croatia)[6]
peat	7	(Molinella [4], Padova [3] – Italy)

Thermal Conductivity Scanning (TCS) apparatus

The Thermal Conductivity Scanning (TCS) apparatus is a high precision non-contact device based on optical scanning of the sample's surface with a focused, mobile and continuously operated heat source in combination with two infrared temperature sensors. The apparatus allows the measurement of profiles of thermal properties along several samples to be performed as well as accounting for any inhomogeneity or anisotropies.

This device requires the samples to be cut in half with a length of at least 5 cm after the preparation process. On the plane surface of the sample, a 2 cm wide black mark is made with non-glossy water based colour along the measuring line. Before every measurement, the device is "warmed-up" for about 30 min and then the "hot" and "cold" sensors are calibrated by measuring a reference standard sample, chosen in accordance with the expected thermal conductivity.

During the analyses a measurement point is taken every 1 mm. The results are a mean value for thermal conductivity, a minimum and maximum value, a homogeneity coefficient and G-function to cover the standard deviation of each run. All samples are measured three times in 72 h to form a superior mean value.

This device has been applied both for rock samples than for over-consolidated clay samples.

The accuracy is reported in Table 3.

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ISOMET 2114 Thermal Properties Analyser

The ISOMET 2114 Thermal Properties Analyser (produced by Applied Precision Ltd) applies the Transient Line Source method, in accordance with ASTM methods (ASTM D5334-00, 2000). The tested material is solicited by a temporary heat flow impulse, in order to analyze the temperature response in time of the sample. This method derives from the transient hot-wire technique (Assael et al., 2010)

This device was used to perform experimental measurements on the unconsolidated sediments; it was selected because it is a hand–held instrument designed for both indoor and outdoor measurements and because it supports both a needle probe sensor, used for slurry and sandy sediments, and the plane probe, used for consolidated samples.

Some of the data was acquired from sediments samples soon after the drilling; the measurements were performed on site, directly on the core samples just collected. In addition, in order to detect the thermal parameters in dry and wet/nearly saturated conditions, the experimental tests were carried out in the laboratories of the Department of Geosciences – University of Padua, Italy.

The accuracy of the measuring device is reported in Table 3

In order to compare the acquired data, some tests on samples of over-consolidated clays were also repeated at the GeoCentre of Northern Bavaria of the Friedrich-Alexander- University Erlangen-Nuremberg, Germany with the TCS already described above.

Modified Taurus Instruments TLP 800

A new device was tested to measure the thermal properties of gravels, in order to overcome the issues related to the clasts size and their variability of the mineralogical and lithological composition. A guarded hot plate Taurus Instruments TLP 800 with a measuring plate of 0.8 × 0.8 m, usually applied to building materials, was modified for this purpose, as presented in (Dalla Santa et al., 2017). The dimensions of the plates allow the testing of a large volume of clasts, allowing an elementary representative volume to be reached. The temperature difference imposed between the hot and the cold plate is lowered from the standard value to 5 °C, in order to minimize the convective contribution on the measured thermal values.

Table 3 reports the measuring accuracy for Taurus Instrument

TLP800 as provided by the producer. The results obtained by the repetition of the performed tests indicates an accuracy of 5.2% for the modified device but, due to the low numbers of measurements performed this can be consider only a first value to be fixed with further additional tests.

2.4. Tested samples

The main part of the tested samples were collected in several European outcrops at the demonstration sites where the new Cheap-GSHPs project technologies were tested ; the rest come from other locations where georeferenced samples were already available. The rock samples have been collected directly from fresh outcrops, where the rocks were not altered nor weathered.

Direct measurements have been performed on samples listed in Table 4, where also the rock formation and the number of specimens available for each category is reported. The tested rocks have been divided into igneous, metamorphic, and sedimentary rocks; the reference names are selected from PAR MAT-DOM, European soil database (ESDB) attribute group, as defined and reported in (Müller et al., 2018).

Part of the samples have been collected at the demonstration sites of the Cheap-GSHPs and Geo4Civhic EU projects and part were already available. For each rock sample the sensor was applied at 5 different measurement points on each face (orthogonal and parallel to the layering), in dry and wet conditions and with the two devices described in par. 2.3.

3. Result and discussion

In order to describe the unconsolidated sediments tested, the following graphs represent the results of the sieve analysis carried out on the gravels and sandy, silty or clayey samples (Fig. 4). Fig. 5 represents the cohesive samples plasticity in the Casagrande Plasticity Chart. The two figures highlight the wide variability of the tested unconsolidated samples.

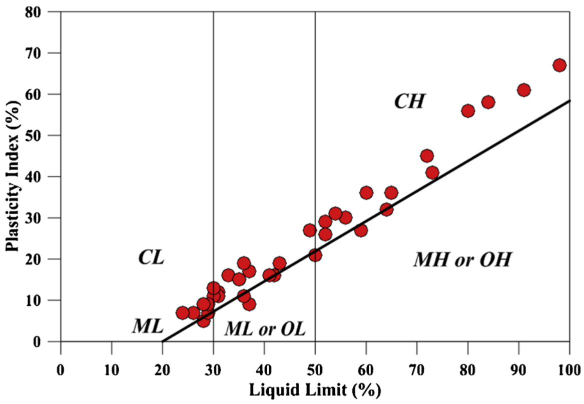

Fig. 5. Representation of the plasticity of the cohesive samples tested in the Casagrande Plasticity Chart. The whole range of the LL and PI are represented.

3.1. Rocks thermal properties database

Fig. 6 represents the values obtained from the measurements performed on the samples (coloured), compared with the variability range acquired from literature (grey). The coloured histograms indicate the median value together with the minimum, the maximum and the most significant percentiles (0.25 and 0.75), when available. This representation provides more information on the distribution of the measured data. As already noted, often, in literature, only the recommended/median value or, in other cases, only the covered range (min, max) are indicated. Therefore only the range of variability of the literature data can be represented, rather than a deeper statistical analysis. The recommended values reported in the literature for each category are represented in Fig. 6a by the black crosses and are compared the median of the measured values. The total amount of measurements performed on samples for each category is indicated by the labels. The experimental measurements have been performed at several moisture content conditions and on sample faces orthogonal or parallel to shistosity, with several devices.

Fig. 6a provides a general overview of the thermal conductivity of rocks. Generally, sedimentary rocks are more influenced by porosity

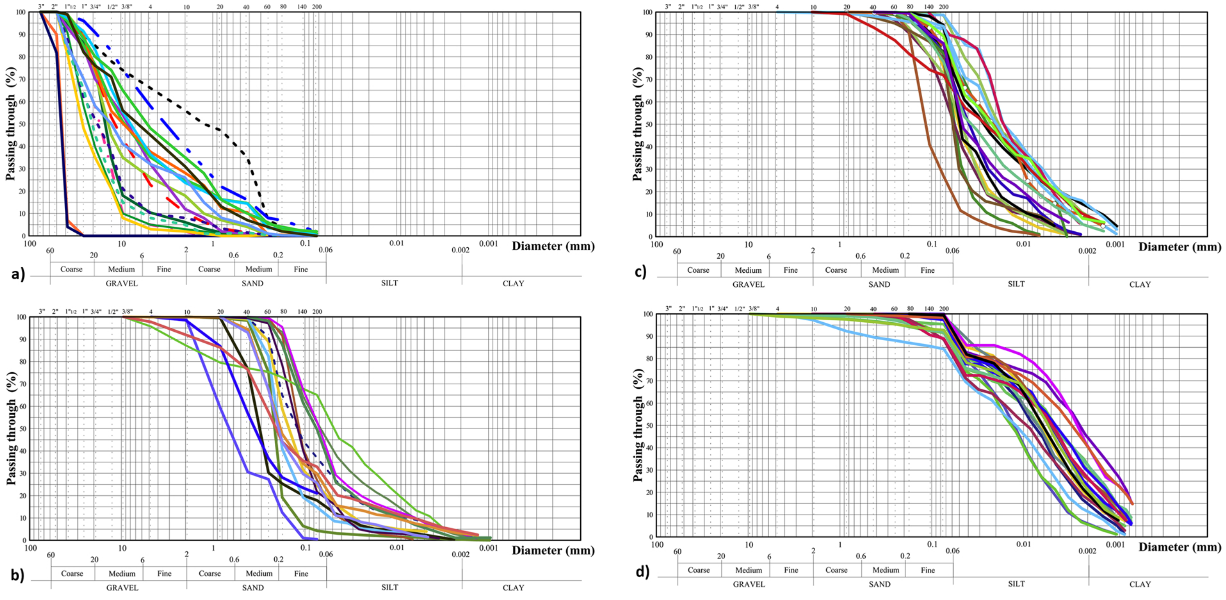

Fig. 4. Granulometric curves of the majority of the unconsolidated samples tested. The samples came from single corings carried out in Molinella, the Cheap-GSHPs project field test site (Galgaro et al., 2017), in the area of Veneto region on the Po-plain in the North-East of Italy, in Zagreb (Croatia), in Pikermi Attiki (Greece) and from the Main river bed sampled in Northern Bavaria (Germany). Fig. 4a represents the gravels, Fig. 4b represents the samples included in the category called 'medium sands', Fig. 4c grouped the sediments in the category called 'silty sands, silts' and, finally, in Fig. 4d are represented the silty clays and clays.

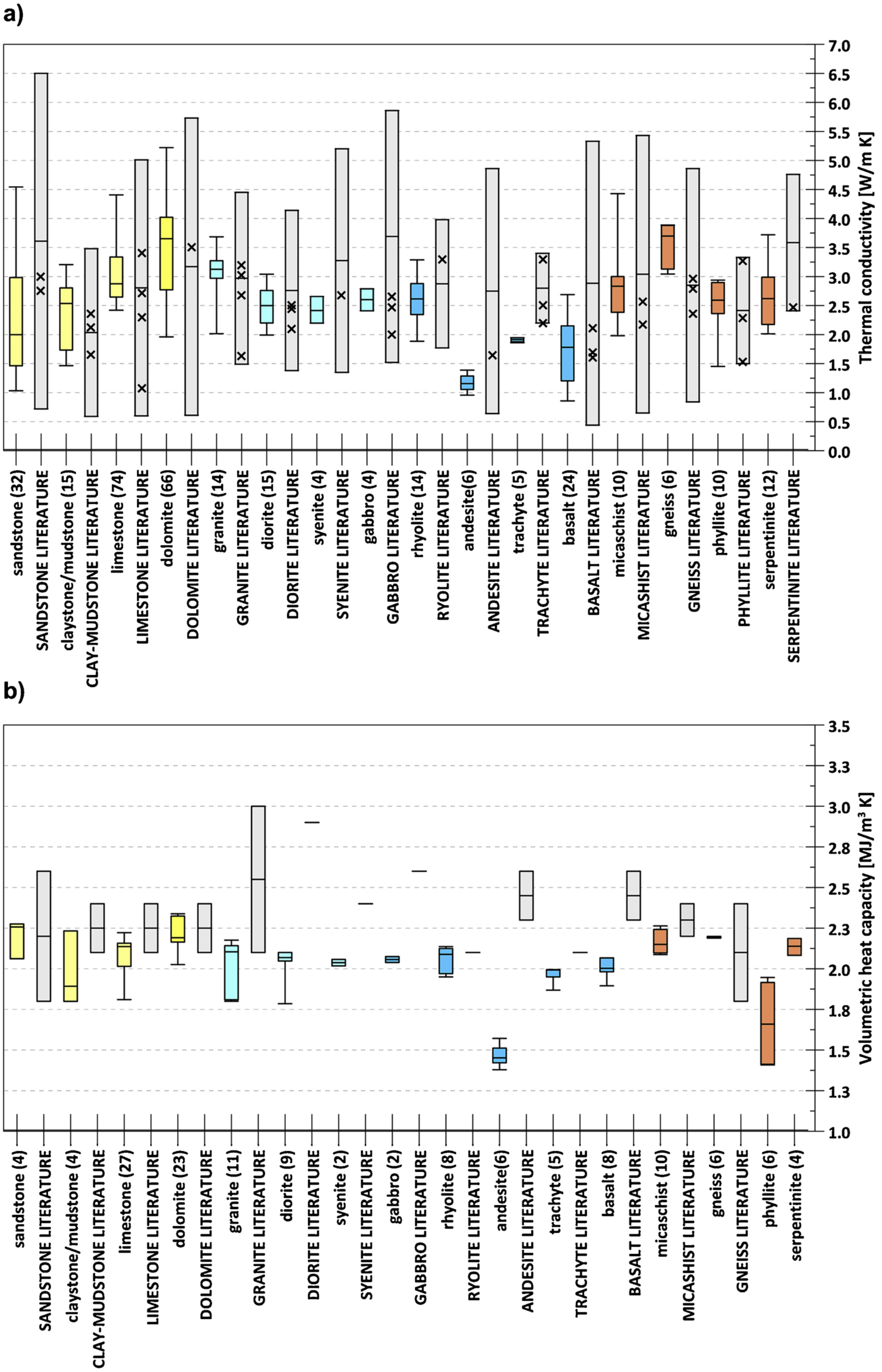

Fig. 6. a) Thermal conductivity values: the coloured bars represent the values obtained from the measurements directly performed on rocks samples, while the grey bars represent the literature data. The black crosses show the recommended values from literature for each category (see Table 1). b) Volumetric heat capacity: the coloured bars represent the values obtained from the measurements directly performed on rocks samples, whilst the grey bars represent the values proposed in the most used guideline (VDI, 2010).

resulting in a wide range of the thermal conductivity values that can be attributed to the influence of texture, the degree of cementation and water content. Intrusive rocks show higher values than extrusive rocks, due to the effect porosity and mineralogical composition have on thermal conductivity. For example, mafic rocks (basalt) have lower thermal conductivity values than the sialic ones (as granitoids), due to the different dominant mineralogical phases (Schön, 2011; Clauser and Huenges, 1995; Clauser, 2011). In plutonic and metamorphic rocks, the thermal parameters are influenced more by the mineralogical association (presence of quartz) than by the effect of porosity that is generally very low. In plutonic rocks, the thermal conductivity is higher where feldspar is present.

In metamorphic rocks porosity is generally very low, thus the thermal behaviour is determined mainly by the mineralogical composition, which is established by the bulk chemical composition as well as the metamorphic grade (Clauser and Huenges, 1995; Schön, 2011; Clauser, 2011). In metamorphic rocks, the higher the percentage of quartz, the higher the thermal conductivity will be. In addition, the rocks tend to show higher thermal conductivity with higher metamorphic grade.

The comparison between literature and experimental data shows that, in the majority of the cases, the range of thermal conductivity obtained from the direct measurements are lower than the ranges reported in the literature (Fig. 6a). This is due to (I) the higher number of samples reported in literature; and (II) the intrinsic variability of rocks grouped in the same lithotype class in terms of different relative abundance of mineralogical phase contents, different texture (i.e. anisotropies, presence of cavities, etc.) and possible mineral grain sizes. As discussed before, the lythotype classes that report wider ranges of thermal conductivity refer to more heterogeneous rock groups (see also Fig. 1).

In other cases, directly measured values are outside the range obtained from the literature, such as serpentinite (Fig. 6a). This may be due to a lack of data present in the literature and different degrees of hydration related to the transformation of primary minerals in serpentine. In these cases, the measured dataset widens the variability range from literature.

Finally, regarding trachyte and andesite, the comparison between measured values and literature data highlights that the latter covers a much wider range. In the case of trachyte, the measured values are outside the range obtained from literature. This can be ascribed to the fact that, in the literature, similar rocks are grouped in the same class (i.e. andesite and basalt, rhyolite and trachyte, etc.). In this case, the new data provides more appropriate thermal conductivity values for these specific lithotypes, also indicating the sampled rock formation (trachyte and andesite)

As for the heat capacity, measured data is less common than thermal conductivity data (Fig. 6b), due to the fact that not all the measuring devices used during this study provide this parameter. In addition, less datasets and information are available in the literature for the heat capacity and in several references (see for example Park et al., 2004; VDI, 2010; Schön, 2011) data is provided in different ways and measuring units. Here, the measured data is compared with the values proposed by the most used guideline in the European countries (VDI, 2010) and are expressed as volume-related specific heat capacity, by also taking density into account. The comparison shown in Fig. 6b demonstrates that in several lithological classes the measured values are outside the range published in literature review. Again, this can be ascribed to the fact that in (VDI, 2010) similar rocks are grouped in the same class (i.e. andesite and basalt, rhyolite and trachyte). The guidelines do not provide clear information about the data source, such as the samples rock formation, the applied measuring devices or the measuring conditions. In addition, this variability can be derived from the actual differences existing between rocks belonging to the same lithology in the relative abundance of the constitutive minerals and differences in the rock texture and mineral grain sizes. Therefore, the proposed dataset adds properly defined values for specific lithotypes. Further comparisons with other literature data will be conducted in future works.

3.2. Unconsolidated sediments thermal conductivity database

Fig. 7 reports the values from the measurements performed on the unconsolidated sediments.

The sediments were divided into ‘practical’ categories. The experimental data have been organized in sediment classes identified based on granulometric classes defined by (1) the predominant dimension of the solid grains (or clasts), (2) the material gradation (poor or rich) and (3) the presence of water. Despite the geotechnical classification of the tested sediments had been performed by means of the sieve analyses and the definition of the Atterberg Limits, the definition of the classes in the database is based on an expert evaluation of the percentage of sand, silt and clay defined by visual description combined with the handling of the sediment and the in its in-situ condition of water content. This is a practical approach, accordingly with the methods followed on site by the operators during the drilling activities for the materials cored. Due to the particular definition of the classes, a direct comparison with the literature data presented in the first part of the paper is not possible.

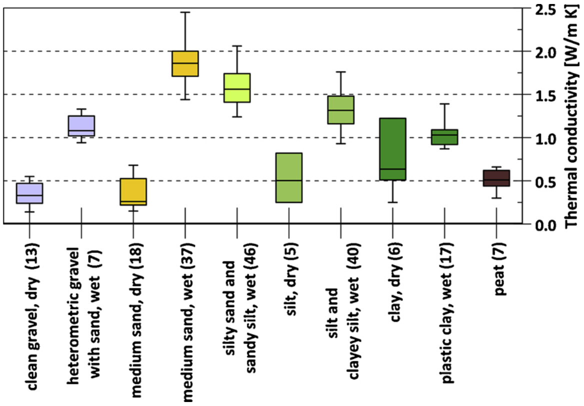

Fig. 7. Thermal conductivity values obtained from the measurements performed on unconsolidated samples (median, minimum, maximum and the most significant percentiles). The numbers indicate the amount of measurements performed for each category (in dry and wet condition, in OC and slurry state, with different devices). Please note that the values reported in saturated conditions for coarser sediments (sand and gravel) have been acquired in presence of standing water, hence they do not include the convective contribution.

The identified classes are reported in Fig. 7 and Table 6. The database includes thermal parameters of gravel, sand, silt and clay as well as the intermediate classes, in order to improve the definition of the thermal properties of defined granulometric sub-categories of sediments. The ‘organic material’ category comprises every material (excluding rocks) with an organic content greater than 5 % of the sample weight including clay or silt with high organic contents as well as peat.

The database defines the thermal conductivity of each sediment class both in dry and saturated conditions, in order to distinguish the thermal behaviour in situ corresponding to above and below the water table. It is important to note that the values reported in saturated conditions for coarser sediments (sand and gravel) have been acquired in presence of standing water: they are values of thermal conductivity and they do not take into account the convective contribution to the exchanged heat provided by the groundwater flow that can achieved in an aquifer on site. In case of significant groundwater flow, an accurate borefield design requires an on-site survey providing the equivalent thermal conductivity that includes the convective contribution.

In addition, please note that the measurements were performed on cored samples, where the microstructure could not be completely preserved. The thermal conductivity on site could be slightly higher in relation to the constraining effect of the surrounding underground and to the sediments texture.

The water content and the degree of saturation are among the driving parameters of the effective thermal conductivity (Beziat et al., 1988; Abuel-Naga et al., 2009; Lydzba et al., 2014). The role played by water content seems to be dominant for unconsolidated sediments (Di Sipio and Bertermann, 2018). The partial filling of the voids with water enhances the conductive heat transport as water has a thermal conductivity about 20 times higher than air. This increase emerges clearly from all the experimental results, regardless the granulometric class considered (gravel, sand, silt or clay). As expected, in dry conditions, the thermal conductivity is higher for clayey sediments than for the sandy ones; this can be attributed to the greater contact surface between the particles due to the tabular habitus of the mineralogical structure of the clays matrix, as opposed to the granular shapes of the sands. In addition, within the inner structure of clays, a certain amount of binding water remains even in anhydrous conditions between the crystallographic planes. As for the sands, in dry conditions the air filling of the pores hampers the heat transfer.

The thermal conductivity of sands displays a wider range of increased thermal conductivity with increasing water content values than that of the cohesive sediments as a result of the increased contact surface between solid grains by the water filled voids. This highlights the importance of considering the local depth of water table, in order to correctly evaluate the thermal properties of sediments where ground heat exchanger installations are planned. In addition, salt content in the interstitial water can affect the sediment behaviour (Dalla Santa et al., 2016b). Higher heat exchange capacity as a result of quartz and of the other minerals present in coarse sediments as opposed to that of phyllosilicates in the main mineralogical phase on silty and clayey materials is also observed. In the experimental data obtained at high water contents, sands have higher thermal conductivity values than the cohesive sediments.

The gravel samples with granulometric gradation show higher thermal conductivity than that of the clean ones, due to the sandy grains infilling the voids. Finally, peat samples and the materials with high organic component, present a very low thermal conductivity.

Fig. 8a presents the comparison between some of the values obtained for sandy sediments at different water content conditions. The results highlight the important role that water plays in heat transfer in porous media by providing continuity between the solid grains and increasing the contact points, promoting the heat transfer processes by conduction.

On the other hand, the comparison conducted between the values obtained for clays in over-consolidated conditions or with slurries shown in Fig. 8b, highlights that the thermal behaviour is significantly affected also by the degree of consolidation. The first group of measurements (OC – in situ) have been performed on the samples collected in Zagreb. The water content was measured and the samples were remoulded and deionized water was added to reach the water content equal to the Liquid Limit (shown in Fig. 5). In this case, despite the water content in the natural over consolidated condition being nearly 4–5% (very low), the thermal conductivity values are higher than in the slurry, even if in this condition the water content is quite high (equal to the Liquid Limit) nearly equal to 30%, 50% or more. This observation demonstrates that the more highly organised and compacted structure present by the sediments in the over consolidated condition results in a higher thermal conductive . As the exchanged heat passes through the contact points between the solid grains, the higher the density of the sample (lower porosity), the higher the thermal conductivity. In the same way, more consolidated sediments or highly organized material show better heat transfer capacity.

3.3. The UNIPD Cheap-GSHPs thermal properties database

Table 6 reports the values of thermal properties included in the Cheap-GSHPs project DSS in order to support users in designing new GSHP systems. The values have been obtained by merging the results measurements performed as part of the project with the ones reported in literature, as represented in Figs. 6 and 7. In the left part of Table 5 the minimum and maximum values of thermal conductivity from literature are reported. The listed values of density and thermal diffusivity are extracted from VDI 4640 as a reference for each lithology. The central part of Table 5 shows the data obtained from experimental measurements; thermal conductivity (minimum, maximum and median values), volumetric heat capacity and density ranges. The right part of the Table reports the UNIPD Cheap-GSHPs values of thermal conductivity. In addition to the range (min, max) that combine literature and experimental data, the proposed recommended value has been evaluated as the average of the recommended values in literature (black crosses in Fig. 6) and the ones obtained from the experimental direct measurements.

The UNIPD-Cheap GSHPs thermal properties database indicates a thermal conductivity range and a recommended value, for each lithotype/unconsolidated sediment class, The data presented can be used to estimate an ‘equivalent’ value of thermal conductivity representative for an entire stratigraphic sequence; the database directly provides the thermal parameter values of each lithology, so that an averaged value for the entire length of the GSHE can be calculated by taking into account the thickness of each deposit.

The database user could assign an estimated value of thermal conductivity to the rocks/sediment in the local geological setting by starting from the suggested values (min, recommended, max values) and by taking into account the features that most affect the rock thermal behaviour such as porosity/density/state of consolidation, water content, texture and mineralogical composition.

Porosity is the parameter of greatest influence on thermal conductivity values both in sedimentary and volcanic rocks with high

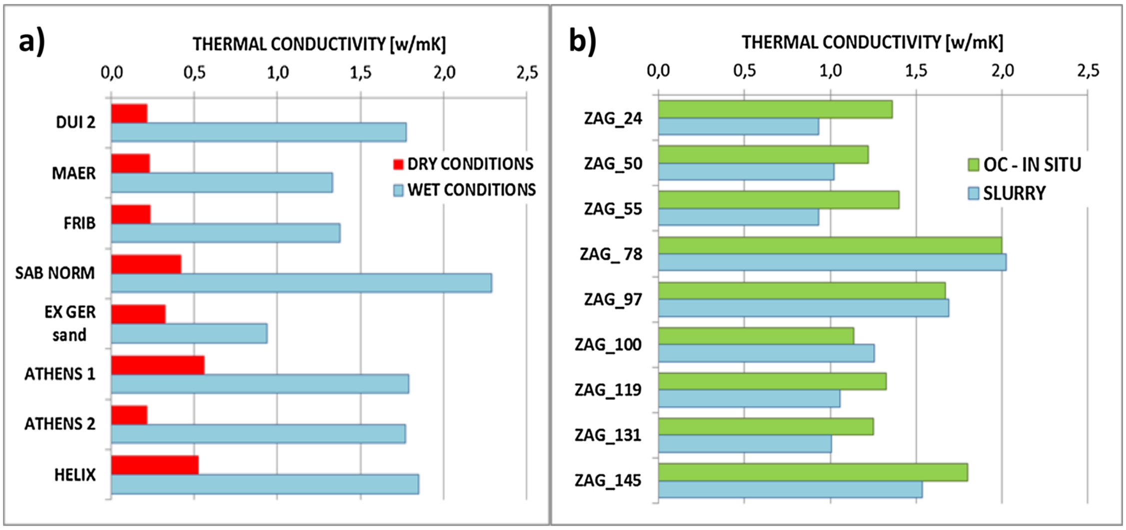

Fig. 8. a) Thermal conductivity of loose fine sediments; comparison between dry and wet conditions. b) Thermal conductivity of loose fine sediments; comparison between the values obtained in the Over Consolidated condition (OC) as in situ, and in the slurry condition.

Table 5
The UNIPD Cheap-GSHPs thermal database.

	From Literature Review				Directly measured					UNIPD-Cheap GSHPs database		
Material	λ $W\ m^{-1}\ K^{-1}$		$\rho\ c_p$ *$MJ\ m^{-3}\ K^{-1}$* [a]	ρ *in 10^3 Kg m^{-3}* [a]	λ $W\ m^{-1}\ K^{-1}$			$\rho\ c_p$ $MJ\ m^{-3}\ K^{-1}$	ρ in 10^3 Kg m^{-3}	λ $W\ m^{-1}\ K^{-1}$		
	min	*max*			*min*	*max*	*REC*			*min*	*max*	*rec.*
Sedimentary rocks	0.59	7.70			1.03	5.62				**0.59**	**7.70**	
conglomerate	1.50	5.10	*1.8-2.6*	*2.2-2.7*						**1.50**	**5.10**	**1.94**
sandstone	0.72	6.50	*1.8-2.6*	*2.2-2.7*	1.03	4.54	2.00	2.06-2.28	2.43-2.66	**0.72**	**6.50**	**2.60**
clay-mudstone	0.59	3.48	*2.1-2.4*	*2.4-2.6*	1.47	3.21	2.54	1.80-2.23	2.70	**0.59**	**3.48**	**2.13**
limestone	0.60	5.01	*2.1-2.4*	*2.4-2.7*	2.42	4.41	2.88	1.81-2.22	2.35-2.80	**0.60**	**5.01**	**2.50**
dolomite	0.61	5.73	*2.1-2.4*	*2.4-2.7*	1.96	5.22	3.65	2.03-2.34	2.47-2.78	**0.61**	**5.73**	**3.58**
marlstone	1.78	2.90	*2.2-2.3*	*2.3-2.6*						**1.78**	**2.90**	**2.04**
gypsum	1.15	2.80	*2.0*	*2.2-2.4*						**1.15**	**2.80**	**1.60**
anhydrite	1.50	7.70	*2.0*	*2.8-3.0*						**1.50**	**7.70**	**4.77**
Igneous rocks	0.44	5.86			0.86	3.29				**0.44**	**5.86**	
granite	1.49	4.45	*2.1-3.0*	*2.4-3.0*	2.02	3.68	3.13	1.80-2.12	2.66-2.73	**1.49**	**4.45**	**2.74**
diorite	1.38	4.14	*2.9*	*2.9-3.0*	1.99	3.04	2.50	1.75-2.10	2.60-2.71	**1.38**	**4.14**	**2.40**
syenite	1.35	5.20	*2.4*	*2.5-3.0*	2.20	2.66	2.41	2.02-2.06	2.69	**1.35**	**5.20**	**2.51**
gabbro	1.52	5.86	*2.6*	*2.8-3.1*	2.41	2.79	2.60	2.08-2.04	2.84	**1.52**	**5.86**	**2.41**
rhyolite	1.77	3.98	*2.1*	*2.6*	1.89	3.29	2.61	1.95-2.09	2.11-2.5	**1.77**	**3.98**	**2.96**
dacite	2.00	3.91	*2.9*	*2.9-3.0*						**2.00**	**3.91**	**2.60**
andesite	0.64	4.86	*2.3-2.6*	*2.6-3.2*	0.96	1.39	1.16	1.38-1.57		**0.64**	**4.86**	**1.43**
trachyte	2.20	3.40	*2.1*	*2.6*	1.86	1.95	1.91	1.87-2.00	2.33-2.63	**1.86**	**3.40**	**2.48**
basalt	0.44	5.33	*2.3-2.6*	*2.6-3.2*	0.86	2.69	1.78	1.89-2.07	2.13-3.02	**0.44**	**5.33**	**1.82**
tuff/tuffstone	1.10	2.59								**1.10**	**2.59**	**1.10**
Metamorphic rocks	0.65	8.15			1.98	4.43				**0.65**	**8.15**	
quartzite schist	1.89	8.15	*2.1*	*2.5-2.7*						**1.89**	**8.15**	**5.18**
micaschist	0.65	5.43	*2.2-2.4*	*2.4-2.7*	1.98	4.43	2.83	2.09-2.26	2.72-2.76	**0.65**	**5.43**	**2.53**
gneiss	0.84	4.86	*1.8-2.4*	*2.4-2.7*	3.04	3.89	3.70	2.19 - 2.2	3.03	**0.84**	**4.86**	**2.95**
phyllite	1.50	3.33			1.45	2.94	2.59	1.41-1.95	2.76-2.82	**1.45**	**3.33**	**2.45**
amphibolite	1.35	3.90	*2.0-2.3*	*2.6-2.9*						**1.35**	**3.90**	**2.90**
serpentinite	2.41	4.76			2.01	3.72	2.62	2.1-2.2	2.63-2.82	**2.01**	**4.76**	**2.52**
marble	0.98	5.98	*2.0*	*2.5-2.8*						**0.98**	**5.98**	**2.50**
nconsolidated sediments												
clean gravel, dry	0.13	0.9	*1.3-1.6*	*1.8-2.2*	0.14	0.55	0.33			**0.14**	**0.9**	**0.4**
heterometric gravel with sand, wet	0.18	3.00			0.94	1.33	1.08			**0.2**	**3.00**	**1.08**
medium sand, dry	0.15	0.90	*1.3-1.6*	*1.8-2.2*	0.15	0.68	0.26	0.41-1.48		**0.15**	**0.9**	**0.4**
medium sand, wet	1.00	2.60	*2.2-2.8*[b]	*1.9-2.3*[b]	1.44	2.45	1.86	1.53-2.27		**1.0**	**2.6**	**1.9**
silty sand/sandy silt, wet	1.20	2.25			1.24	2.06	1.56	1.85-2.48		**1.20**	**2.25**	**1.62**
silt, dry	0.26	1.09	*1.5-1.6*	*1.8-2.0*	0.25	0.82	0.50	1.37-1.52		**0.25**	**1.09**	**0.55**
silt and clayey silt, wet	0.82	2.60	*2.0-2.8*[b]	*2.0-2.2*[b]	0.93	1.76	1.32	1.84-2.43		**0.82**	**2.60**	**1.45**
clay, dry	0.25	1.52	*1.5-1.6*	*1.8-2.0*	0.25	1.22	0.64	0.49-1.38		**0.25**	**1.52**	**0.64**
plastic clay, wet	0.60	1.90	*2.0-2.8*[b]	*2.0-2.2*[b]	0.87	1.39	1.03	0.62-2.67	from slurry to OC	**0.60**	**1.90**	**1.10**
organic materials: peat	0.2	0.7	*0.5-3.8*	*0.5-1.1*	0.30	0.66	0.51	0.32-0.78		**0.2**	**0.7**	**0.51**

[a] The listed values of density and thermal diffusivity are extracted from VDI 4640 as reference for each category.

[b] The values are reported for water-saturated conditions.

porosity values due to their genetic conditions (Clauser and Huenges, 1995; Schön, 2011; Clauser, 2011). Porosity and thermal conductivity are typically inversely proportional parameters. Thermal conductivity is also affected by density that is determined by mineralogical composition, porosity, pore filling (water or air) as well as pressure and temperature during the rock formation process. Density and thermal conductivity are directly proportional. Hence, the more porous rock samples will display thermal conductivity values in the lower part of the proposed range. For the same reason, the presence of water in the pore spaces leads to higher thermal conductivity. Therefore, in dry condition the lowest thermal conductivity values should be selected from the proposed range. In case of texture anisotropy, rock thermal conductivity is higher parallel to shistosity.

Similarly for the unconsolidated sediments: in dry conditions, the lowest thermal conductivity value should be chosen from the proposed range, whilst the highest thermal conductivity values should be chosen in saturated conditions. In the case of loose sands and slurry clays (low density), low thermal conductivity values are more likely; whilst, with higher density and compacted samples, higher thermal conductivity values are applicable. The highest values of the proposed range should be considered for the latter. In addition, please note that the thermal conductivity on site could be in the higher part of the range, in relation to the constraining effect of the surrounding underground and to the sediments texture. Higher grading in sediments results in higher thermal conductivity, as a result of the smaller particles filling the voids between the coarser grains.

It is important to note that, in the case of a BHE intersects an aquifer, the groundwater flow significantly affects the thermal exchange between the ground and the BHE (Chiasson et al., 2000). Groundwater flow in the aquifer, allows the transfer of heat to happen not only by conduction but also by convection. For this reason, the values proposed in this database are not applicable for the geological deposits hosting an aquifer or where significant groundwater flow is present. In these cases, only a Thermal Response Test can provide the correct heat exchange capacity of the whole system.

4. Conclusions

The European project Cheap-GSHPs provides a DSS to assist stakeholders in planning and designing new closed-loop GSHP systems. For this purpose, the most relevant aspects that have to be taken into account when designing a new closed-loop GSHP system are integrated in the DSS by means of software tools linked to a series of datasets to provide the designing parameters required by the user. Thermo-geological properties including the local thermal properties of the ground and the ground temperature profile, play a fundamental role in the design of ground heat exchangers as these determine the thermal exchange capacity, affect the energy performance of the whole system and control the investment and operational costs. Hence, they are critical information to evaluating the feasibility of shallow geothermal projects.

The thermal data presented in this paper has a practical goal in providing the necessary thermal property values of the geological conditions through a database created as part of the Cheap-GSHPs project. The data can be very useful for preliminary GSHP feasibility studies and design. The most important elements are:

1) The UNIPD Cheap-GSHPs database for geological materials represents a collection of the state of the art on thermo-physical information, and intended as an international reference on the thermal properties for shallow geothermal systems. The database integrates internationally used data such as that published in the VDI and ASHRAE guidelines as well as new additional literature references.
2) More than 250 samples of unconsolidated sediments and rock samples have been measured in order to extend the datasets in the literature. The UNIPD Cheap-GSHPs database proposes a recommended value, calculated as the average of the recommended values provided by the literature and the ones obtained from the measurements undertaken as part of the project. In addition, the minimum and maximum values illustrate the possible variation of thermal conductivity due to the wide variability and heterogeneity in natural earth materials.
3) The new data provided, widens the literature variability range of thermal conductivity for phyllite, and more precisely defines the ranges covered by andesite, trachyte and serpentinite.
4) A new dataset of volume-related specific heat capacity is also provided for specific lithotypes.
5) The database lists the thermal properties for unconsolidated sediments that are divided into ‘practical’ categories by taking into account the granulometry and the moisture content.
6) The new data on the thermal properties of gravels acquired using an updated device developed as part of the project and included in the database represent a significant addition to international published data. Please, note that these are thermal conductivity values, hence they do not take into account the convective contribution provided by groundwater flow.

When the local stratigraphic sequence intersected by a BHE is known at the design phase of a new borefield, the database allows the thermal parameters of each identified deposit to be assigned, hence the overall thermal conductivity of the intersected lithologies can be estimated weighting the values on the thickness of each deposit.

The use of the information from the UNIPD Cheap-GSHPs database provides a starting base of knowledge for preliminary estimation of the feasibility of a new GSHP system. However, prudent GSHP design should requires site-specific data and surveys for an accurate feasibility study or design. Thermal Response Tests can be necessary for further characterization of the thermo-physical conditions and heat exchange potential of the local geological setting, in particular when the boreholes cross flowing groundwater.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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