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THERMAL PROPERTIES VARIATIONS IN ALLUVIAL SEDIMENTS OF THE PO RIVER (NORTHERN ITALY)

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EXTENDED ABSTRACT

Obiettivo principale della ricerca è quello di valutare la possibile influenza di alcuni parametri fisici, come la composizione granulometrica, la porosità, la densità apparente e il contenuto d'acqua, sui valori della conducibilità termica di materiali sciolti.

Al fine di ottenere il più ampio spettro granulometrico possibile, sono stati selezionati diversi campioni provenienti dai depositi alluvionali del bacino idrografico padano (nord Italia). La componente clastica di ogni campione è stata separata in intervalli di dimensioni standard (phi) e successivamente ogni classe è stata analizzata separatamente. La composizione granulometrica dei campioni analizzati copre un ampio spettro che varia dai ciottoli fini ($-3 < \varphi < -2$) alla sabbia molto fine ($+3 < \varphi < +4$).

I test termici, realizzati presso il laboratorio GeoTh dell'Università di Ferrara, sono stati condotti a diversi intervalli di saturazione di acqua (0-100%). L'analisi integrata dei dati attenuti ha messo in evidenza a) che la superficie di contatto tra i granuli assume un ruolo importante nella modalità di trasmissione del calore; b) un contenuto di quarzo fino al 60% non è sufficiente ad influenzare i valori di conducibilità termica sia in condizioni secche che sature; c) l'impatto dominante del contenuto di acqua nei campioni sull'aumento dei valori della conducibilità termica. Relativamente a quest'ultima conclusione, nei terreni sabbiosi da fini a grossolani ($+3 > \varphi > 0$) si osserva un rapido aumento della conducibilità termica per contenuto volumetrico d'acqua inferiore al 30% m^3/m^3, mentre nelle sabbie fini ($+3 > \varphi > +2$) si verifica un graduale aumento della conducibilità termica fino a un grado di saturazione del 45-50% m^3/m^3.

Inoltre, per ciascuna classe granulometrica, sulla base dell'elaborazione statistica dei dati analitici ottenuti, è stata proposta una relazione empirica che permette di rappresentare la distribuzione dei dati. La valutazione del comportamento termo-fisico dei depositi alluvionali del fiume Po potrebbe fornire un punto di partenza per la modellazione numerica del trasporto di calore in diverse condizioni litologiche e di saturazione del sottosuolo.

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ABSTRACT

This work aims to highlight the possible influence of grain size, porosity, bulk density, and water content on thermal conductivity and to investigate possible empirical relationships. To achieve this goal, we created an experimental laboratory based on the guarded hot plate method to measure the thermal conductivity of unconsolidated materials. Loose sedimentary deposits were selected from Po Valley (Italy), while the clastic component was separated into standard size ranges and each class tested separately. This allowed us to relate thermal conductivity and grain size while taking into account also other petro-physical parameters. In order to obtain the widest possible granulometric spectrum, investigated samples are in the range from fine pebbles to very fine sand ($-3 < \varphi < +4$). These materials were also analysed to identify the present mineral phases. Thermally tests were conducted at different water saturation degrees. The results were processed using statistical techniques and compared with literature data and empirical equations.

KEYWORDS: thermal conductivity, grain size, water content, shallow geothermal energy.

INTRODUCTION

Renewable energies are becoming increasingly important in everyday life, not only for electricity generation, but also for heating and cooling of buildings. Geothermal energy, despite currently being underutilized, has significant potential. Specifically, low-enthalpy or shallow geothermal energy could play a fundamental role in the energy transition, as most CO_2 emissions in Europe come from heating and cooling of buildings (EUROPEAN COMMISSION, 2022; IEA, 2022). At this regard, geothermal energy is one of the most promising solutions due to its renewable and sustainable nature, lack of greenhouse gas emissions, and absence of air and soil pollution.

Indeed, low-enthalpy geothermal systems could produce energy continuously; 24 hours a day and every day of the year, thanks to the roughly constant underground temperature down to a depth of approximately 150 m. This makes low enthalpy geothermal energy a reliable and stable energy source that can be effectively integrated with other renewable sources such as solar or wind energy, which are in turn quite variable in intensity during the day and the seasons (*e.g.*, EL HAJ ASSAD *et alii*, 2021; TINTI *et alii*, 2023; RAPTI *et alii*, 2024). Although geothermal open-loop systems in sedimentary formations may provide a sustainable solution where the geothermal potential and heat demand coincide, these technologies are subject to some technical problems, including groundwater recession, corrosion and scaling (GIZZI, 2021). On the other hand the use of shallow geothermal energy for cooling and heating of the buildings can reduce the dependence on fossil energy sources, thus contributing to mitigate their environmental impact.

However, to evaluate the heat transfer modes from/to the subsoil and consequently the long-term sustainability of any shallow geothermal plant, a good knowledge of the hydrogeological and thermophysical model of the underground is necessary (VIENKEN *et alii*, 2019; NAICKER & REES, 2019; TSAGARAKIS, 2020). In particular, the thermal conductivity of unconsolidated natural materials such as gravel, sand, silt, and clay are strongly influenced by i.e. their grain size distribution, the degree of water saturation or the temperature (EWING & HORTON, 2007; DONG *et alii*, 2015; MIDTTØMME & ROALDSET, 1998; CÔTÉ & KONRAD, 2005; CHEN, 2008; HAIGH, 2012; LU *et alii*, 2007; FAROUKI, 1981). In porous media, the thermal properties are determined by the volume fraction of each constituent material (YUN & SANTAMARINA, 2007; FAROUKI, 1982; JOHANSEN, 1977; BERTERMANN *et alii*, 2018) such as soil particles ($\lambda_s > 3.0$ W/m·K), water (λ_w; 0.56 W/m·K) and air (λ_a; 0.026 W/m·K). Heat conduction in the presence of a temperature gradient occurs mainly by conduction, whereas in highly permeable soils, heat transfer by convection could play a significant role.

Particularly in dry unconsolidated materials, heat is conducted primarily through the solid phase and limited by the contact points between solid particles; whereas in the case of the presence of water even without a complete saturation of the pores, transient water bridges connecting the space between neighbouring particles increase the contact areas between solid volumes and thus greatly expand the heat conduction transfer paths. In this way, the 'particle-particle' conduction mechanism is transformed into 'particle-water-particle' mechanism, which causes a rapid tendency for the thermal conductivity of the porous medium to increase (*e.g.* ALRTIMI *et alii*, 2016; LIU *et alii*, 2024).

Since conduction is the prevailing phenomenon in relation to the method used in the laboratory, thermal conductivity (λ, in W/m·K) of materials can be calculated by the following equation:

$$\lambda = (Q \cdot L) / (A \cdot \Delta T) \tag{1}$$

where Q, is the amount of power out coming in a system (W), passing through a cross-section A (m^2), and causing a temperature difference, ΔT (K), over a distance L (m).

The aim of this study is to examine the physical-thermal properties and their changes in different types of soil with grain size ($-3 < \varphi < +4$), under the same environmental conditions and under different moisture content water conditions from 0% to 100% (m^3/m^3). For this purpose, more than 100 samples were prepared by varying the reference material and the water content for testing in the laboratory.

DATA AND METHODS

For the purpose of the present research, several samples were collected from the alluvial deposits of the Po River (Piacenza area; northern Italy). The main criterion applied in the selection and collection of samples was their granulometric characteristic, that is to say to contain as more as possible grain-size classes with values of diameter φ variable between −3 (8 mm) and +4 (0.062 mm). To determine the particle size distribution, all samples were initially purified of organic impurities. Subsequently, by applying the analytical procedure of mechanical sieves and eventually gravity sedimentation technique, the different particle size fractions representative of each sample were calculated. Figure 1 shows the cumulative curves of 'natural' not-sieved analyzed samples; where we may observe that, the grain size composition varies from predominantly gravelly (A) to medium (B) and fine sands (C).

In the second phase, each sample was subjected to a separation based on grain diameter (φ) applying sieves methods. In this way, subclasses of sediments were obtained characterized according to Wentworth (1922) as fine pebbles ($-3 < \varphi < -2$), very fine pebbles ($-2 < \varphi < -1$), very coarse sand ($-1 < \varphi < 0$), coarse sand ($0 < \varphi < +1$), medium sand ($+1 < \varphi < +2$), fine sand ($+2 < \varphi < +3$) and very fine sand ($+3 < \varphi < +4$).

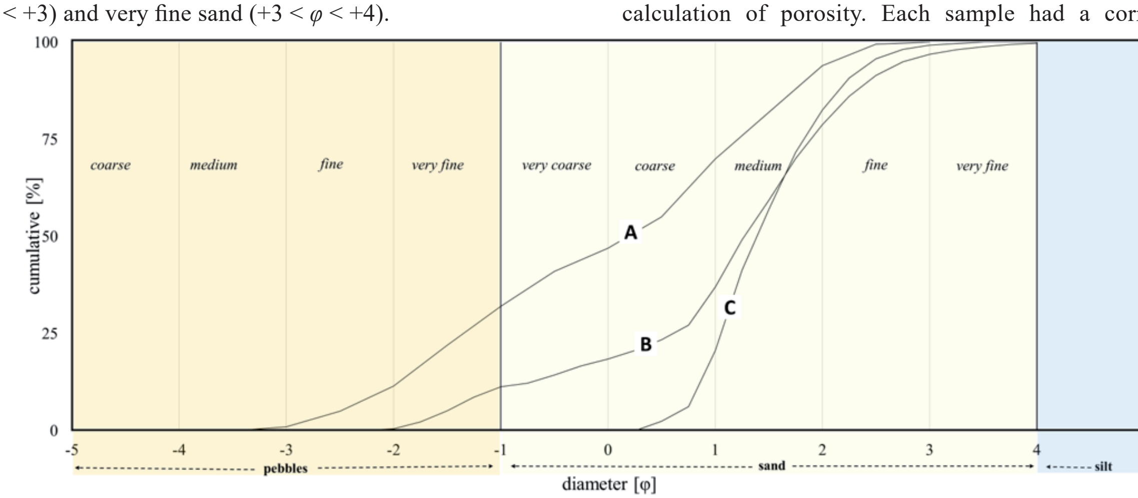

Fig. 1 - Cumulative grain size curves of no-sieved soil samples

Also, the identification of the main mineralogical phases characterizing the soils (in both sieved and unsieved materials) was performed through the application of X-ray diffraction (XRD) techniques.

Finally, thermal conductivity measurements were carried out in all samples by applying the Infinite Line Source (ILS) method and under different saturation conditions (from 0% to 100%) at the Geoth laboratory by using a configuration based on the one-dimensional heat conduction in steady-state regime (Rapti *et alii*, 2022). In particular, the setup consists of a cylinder to contain the sample, the side wall is cylinder in PVC characterized by very low conductivity (0.17 W/m·K) while the base is metallic (aluminium) with very high conductivity to guarantee heat transmission with negligible thermal resistivity. The cylinder is thus filled with the material to be tested, which was previously oven-dried at 60 °C or 105 °C depending on the particle size and the crystal lattice. The amount of sample inside the cylinder is about 1 kg. The sprinkling technique was adopted for filling the testers.

Aluminium films of microns thickness were inserted at regular intervals to interrupt convective motions of the fluid within the pores (air and/or water) potentially created during the heating phase. Once the sample was fully loaded, an additional film of aluminium was placed on top, and the cylinder was thermally insulated both laterally and at the base with materials having a thermal conductivity less than 0.034 W/m·K. During the sample preparation, PT 100 sensors were positioned within the cylinder at different distances from the base and located at the centre of the cylinder to minimize any possible edge effect during the measurement.

After weighing the material inserted into the sample holder and relating it to the internal volume of the cylinder, we obtained dry bulk density values. The methodological approach described by Missimer and Lopez (2018) was adopted for the calculation of porosity. Each sample had a corresponding set of porosity and water saturation (% m^3/m^3). The thermal conductivity tests were carried out at different porosity and saturation conditions. The average duration of each test was approximately 12 hours. In this way, it was possible to obtain the thermal conductivity under dry conditions, wet conditions in different percentages and fully saturated conditions. A total of 108 thermal conductivity tests were performed.

RESULTS

In order to consider some possible experimental variability introduced during the sample preparation, for the evaluation of the thermo-physical parameters, 6 identical samples were analysed contemporaneously by measuring porosity, bulk density and especially the thermal parameters needed for calculating the thermal conductivity according to equation (1). This statistical procedure was applied to each undifferentiated material (A, B, C) either under dry and water saturated conditions. The results of the analyses in terms of minimum and maximum values for each set of 6 samples measurements are shown in Table 1.

parameter	unit		A	B	C
porosity	[%]	min	23	33	33
		max	27	36	35
bulk density	[kg / m^3]	min	2015	1630	1455
		max	2100	1660	1555
mineralogical composition	[%]	Qz	45	60	60
		Pl	12	11	16
		K-Feld	2	7	5
		carbonates	25	7	5
mean thermal conductivity	[W/mK]	dry	1.2	0.9	0.9
		wet	3.3	2.9	3.1
grain size	[%]	gravel	35	10	0
		sand	65	90	100

Tab. 1 - Main physico-thermal properties of unsieved materials (carbonate content is referred to the sum of calcite, dolomite and ankerite)

From the particle size point of view, sample A is composed of 56% sand and 35% gravel; the sand content is greater in sample B (90%) and C (100%). For each sample, the porosity values show small fluctuations; sample A has the lowest values in the range 23-27%, while in B and C the values are similar with variations between 33 and 36%.

Bulk density has the lowest value in sample C with variations between 1455 and 1555 kg/m^3; intermediate values in B (1630-1660 kg/m^3); and highest in A with variations between 2015 and 2100 kg/m^3. The average thermal conductivity under dry conditions is 1.2 W/m·K in A, and 0.9 W/m·K in samples B and C; while under 100% saturated conditions it assumes average values of 2.9, 3.1 and 3.3 W/m·K in samples B, C and A respectively. The calculated thermal conductivity values are higher than those suggested in the VDI 4640 (2010) standards in both water saturated (2.4 W/m·K) and dry (0.4 W/m·K) conditions.

As regards the mineralogical composition, in sample A quartz (45%) and carbonates (25%) prevail; while samples B and C are mainly composed of quartz (60%). In all samples, the percentage of plagioclase and feldspars is similar with average values about 13% and 5%, respectively.

Meanwhile, as can be seen in Table 1, the thermal conductivity values under both saturated and unsaturated conditions are mainly affected by the particle size composition of the samples and the contact between the grains expressed by the porosity and bulk density parameters; while no collations with quartz content are evident.

Subsequently, the samples were sieved and divided into one phi (1-φ) classes; and for those belonging to the same grain size class the same methodological approach was carried out as described for the unsieved soil samples. In this phase for better evaluating the influence of the degree of saturation of the sediments on the thermal conductivity, tests were carried out by gradually saturating the samples until complete saturation.

All average values are listed in Table 2 and represented in Figure 2 from where it is possible to observe the following:

a) in all analysed samples and in all particle size classes the porosity is around 40% with small fluctuations;

b) in samples composed of coarser particles (fine pebbles; $-3 < \varphi < -2$) the percentage of carbonates is 58% decreasing to 45% and 36% in very fine pebbles ($-2 < \varphi < -1$) and very coarse sand ($-1 < \varphi < 0$), respectively. Similar trend but with a very small range of values (21-25%) is observed also for quartz with percentages in the order of 23%. Plagioclases and feldspars show no appreciable fluctuations with average values of about 5 and 3%, respectively.
For smaller grain sizes between coarse and very fine sand ($0 < \varphi < +4$) in the mineralogical composition of the samples, quartz prevails with fluctuations between 36% (very fine sand; $+3 < \varphi < +4$) and 59% (coarse sand; $0 < \varphi < +1$). Again, a progressive decrease in the content of this mineral is observed as the grain size fraction decreases. As for the other particle size fractions, the percentage of carbonates varies from 6 to 17%; of plagioclase between 7 and 12%, while feldspars are in the range 5-9 %.

c) The mean bulk density shows fluctuations between 1427 to 1631 kg/m^3; with mean value of:

i. 1602 kg/m^3 for $-3 < \varphi < 0$; which corresponds to the particle

parameter	unit		[-3<φ<-2]	[-2<φ<-1]	[-1<φ<0]	[0<φ<1]	[1<φ<2]	[2<φ<3]	[3<φ<4]
mean porosity	[%]		42	43	43	40	39	42	42
mean bulk density	[kg / m^3]		1580	1595	1631	1499	1460	1427	1430
mean thermal conductivity	[W/mK]	dry	1.1	0.9	0.9	0.9	0.9	0.8	0.8
		wet	3.2	2.8	2.8	3.1	3.0	2.7	2.8
mineralogical composition	[%]	Qz	25	24	21	59	51	43	36
		Pl	5	6	5	12	16	13	7
		K-Feld	2	6	3	5	6	9	6
		carbonates	58	45	36	15	6	14	17

Tab. 2 - Average values for each particle size fraction relative to porosity (%; n. 42), bulk density (kg/m3; n. 42); thermal conductivity in dry conditions (W/m·K; n. 42), thermal conductivity in saturated conditions (W/m·K; n. 42); and mineralogical composition (%; n. 7); where n, is the number of measurements, tests or analyses

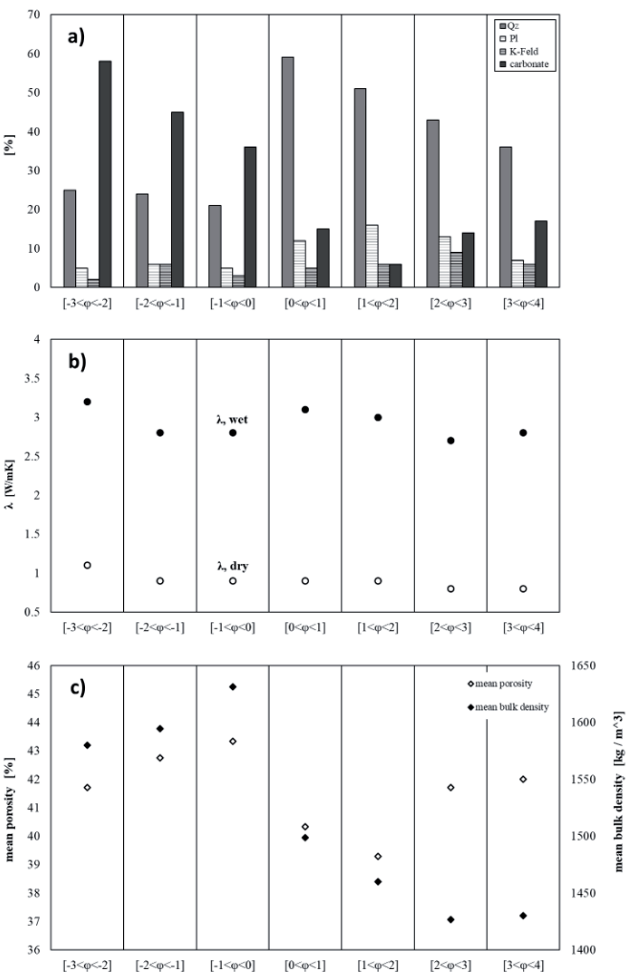

Fig. 2 - *Particle size fraction versus a) mineralogical composition (%); b) average thermal conductivity in dry and wet conditions (W/m·K); and c) average porosity (%) and bulk density (kg/m³)*

size fractions with higher calcite content. The relationship between porosity and bulk density is expressed by the linear equation:

porosity = 0.028[bulk density] - 2.81, with $R^2 = 0.84$

ii. 1454 kg/m³ in the samples where quartz prevails in the mineralogical composition of the samples ($0 < \varphi < +4$); while the relationship between porosity and bulk density is expressed by the second-degree polynomial equation: *porosity = 0.0015[bulk density]² - 4.29[bulk density] + 3196*, with $R^2 = 0.94$.

The differences in bulk density agree with the analytical considerations for dry grain density estimates of sedimentary minerals reported in Horai (1971), Serra (1979) and Deer *et alii* (1969).

d) Thermal conductivity under dry conditions shows values between 0.8 and 1.1 W/m·K; while under saturated water

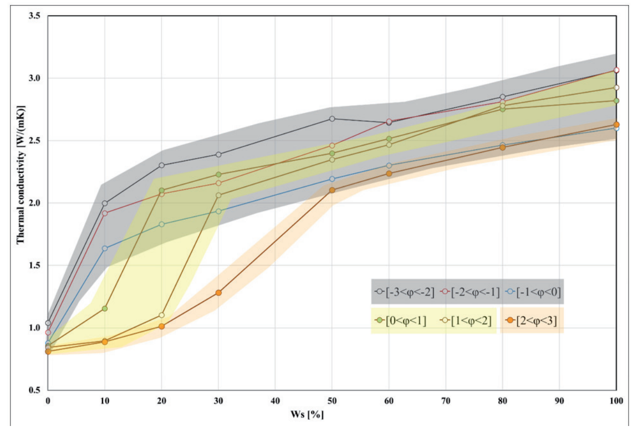

Fig. 3 - *Thermal conductivity versus degree of water saturation (Ws) in % m³/m³; for each particle size classes*

conditions (100%) an increase of about 325% is observed with values ranging between 2.7 and 3.2 W/m·K.

The following equation shows the relationship between thermal conductivity under saturated and unsaturated conditions: $\lambda_{dry} = 1.5\ \lambda_{wet} + 1.56$, with $R^2 = 0.65$.

From the obtained analytical data, a trend in thermal conductivity with granule diameter (φ) is not clearly evident.

It is well known that in granular sediments

$$\lambda_{air} < \lambda_{dry\ soil} < \lambda_{water} < \lambda_{saturated\ soil}.$$

Therefore, in the investigated (predominantly sandy) soils, under anhydrous conditions, the thermal conductivity is drastically reduced due to the presence of air in the pores. As saturation increases, air is gradually replaced by water in the pore system and consequently, thermal conductivity values increase, thus inducing a better condition for heat transfer.

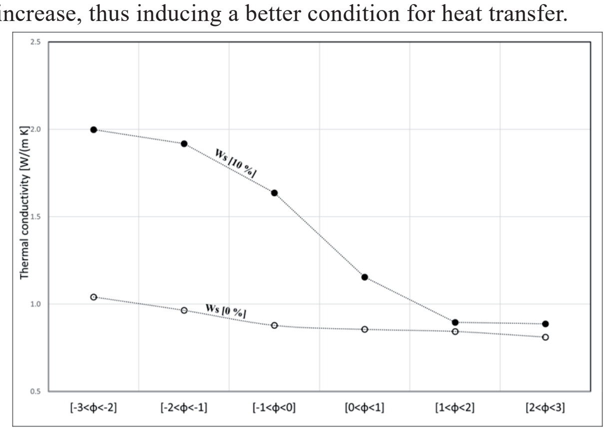

Fig. 4 - *Thermal conductivity versus particle size classes for degree of saturation in water (Ws) of 10% m³/m³*

The curves represented in Figure 3 show the average thermal conductivity values referring to the degree of water saturation (W_s) 10% m³/m³ for the several grain size ranges tested during this research. What is clear from these curves is the systematic increase of the thermal conductivity with increasing water saturation. It is also noteworthy that, when including only a small amount of water, say 10-20% m^3/m^3, thermal conductivity is drastically affected by the grains class, being <1.0 W/m·K for fine sand ($+2 < \varphi < +3$) becoming > 2.0 W/m·K for very coarse sand and gravels ($-3 < \varphi < 0$). In contrast, when water saturation is greater than ca. 50% m^3/m^3, the influence of the grain size on the thermal conductivity is much reduced with a general variation of less than 0.5 W/m·K.

In fact, the maximum value of thermal conductivity reaches 2 W/m·K (100 % increase with respect to λ_{dry} conditions) in the coarsest soils to decrease rapidly towards soils with smaller granule diameters. Particularly for fine sands, the average conductivity is around 0.9 W/m·K, which corresponds to a 9 % increase compared to its value under dry conditions (λ_{dry}).

This phenomenon could probably be attributed to the fact that finer-textured soils are made up of particles that, if we consider an elemental volume, have a cumulatively greater surface area than in case of coarser-textured soils. As a result, more water is required to create water bridges between the particles and to cause a significant increase in thermal conductivity as previously mentioned. Conversely, with the same degree of saturation, in soils consisting of coarser particles, the increase in thermal conductivity is much faster.

At this regard, in Figure 3 it is possible to observe that for fine sands ($+2 < \varphi < +3$), the thermal conductivity increases very slowly until saturation of about 30% m^3/m^3, with values that are systematically below 1.5 W/m·K, while a value of 2.0 W/m·K is obtained only at saturation levels between 45 and 50% m^3/m^3. In contrast, medium and coarse sands ($0 < \varphi < +2$), reach 2.0 W/m·K at lower saturation conditions, between 15 and 3% m^3/m^3.

Saturation values between of 10-15% m^3/m^3 for fine to very fine pebbles and very coarse sand ($-3 < \varphi < -2$; $-2 < \varphi < -1$; $-1 < \varphi < 0$), 15-20% m^3/m^3 for coarse sand ($0 < \varphi < +1$), 25-30% m3/m3 for medium sand ($+1 < \varphi < +2$); and 45-50% m^3/m^3 for fine sand ($+2 < \varphi < +3$) can be considered representative of the field capacity of each soil. From these thresholds upwards, as the pore water content of the voids increases, the rate of increase in thermal conductivity is smaller, reaching values between 2.6 and 3.0 W/m·K at 100% m^3/m^3 saturation.

Finally, based on the statistical processing of the analytical data, Table 3 shows the second-degree equation that best represents the distribution of the analytical data and the correlation coefficient (R2) for each grain size class.

φ	equation	R^2
[-3<φ<-2]	$\lambda=0.0002(Ws)^2 + 0.038(Ws) + 0.39$	0.88
[-2<φ<-1]	$\lambda=0.0002(Ws)^2 + 0.034(Ws) + 1.28$	0.91
[-1<φ<0]	$\lambda=0.0002(Ws)^2 + 0.032(Ws) + 1.12$	0.93
[0<φ<1]	$\lambda=0.0003(Ws)^2 + 0.045(Ws) + 0.94$	0.93
[1<φ<2]	$\lambda=0.0002(Ws)^2 + 0.043(Ws) + 0.65$	0.95
[2<φ<3]	$\lambda=0.0001(Ws)^2 + 0.031(Ws) + 0.63$	0.96

Tab. 3 - Relationship between thermal conductivity and degree of saturation in water for each class of φ

CONCLUDING REMARKS

The several tests carried out for analyzing the thermophysical behavior of the alluvial sediments of the Po River, both as such and separated into granulometric classes from $\varphi = -3$ to $\varphi = +4$ show that:

a) the contact surface between the granules plays an important role in the mode of heat transmission, while even a quartz content up to 60% fails to play a dominant role on thermal conductivity values in both dry and saturated conditions;
b) the dominant impact of water content on thermal conductivity;
c) for fine to coarse sand soils ($-3 < \varphi < 0$) a rapid increase in thermal conductivity with volumetric water content of less than 30% m^3/m^3;
d) for fine sands ($+2 < \varphi < +3$), a gradual increase in thermal conductivity up to a saturation degree of 45-50% m^3/m^3.

Finally, the identification of the thermal behavior of granular materials in the Po River and the data obtained could provide a starting point for numerical modelling of heat transport under different subsurface saturation conditions.

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