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ANALYSIS OF THE THERMAL RESISTIVITY OF COMPACTED SILTY SOILS FOR DESIGNING UNDERGROUND CABLE SYSTEMS

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ABSTRACT

This paper investigates the thermal conductivity of silty soils, when in compacted state. This aspect is especially relevant for designing underground electrical cables that are used to transmit energy from the sources to users. The high importance of the state of the soil is underlined by its role in the heat exchange efficiency, acting as a transfer medium between the electrical cables and the adjacent soil. The main approach of this paper is to review the grading size analyses of soils used for compaction and then, through laboratory testing methods to assess the thermal resistivity of the resulted material at different compaction states. The testing method employed for characterizing the material from the thermal resistivity standpoint is the thermal needle method, a method usually employed both on-site and in laboratory. The study examines silty soils with similar grading distribution and different compaction states, analysing their impact on thermal conductivity. The aim of this research is to establish the influence of the compaction state on the thermal resistivity of silty soils and, also, to offer some guidance in the choice of the soil used for filling the trenches dug for installation of cables.

Keywords: thermal conductivity, silty soils, electrical cables, heat transfer.

INTRODUCTION

When considering renewable energy, wind and solar power are known as one of the most sustainable and efficient ways for replacing the fossil fuels. As this branch of industry progresses, more technical challenges arise, one being adaptation of the infrastructure for energy transfer from source to users. Any new infrastructure built is made of systems of underground cables which need to be in accordance with environmental conditions and regulations specific to the site it is installed at. A detailed understanding of the soil is essential for designing a reliable and durable cable system which is critical to obtaining a performant and reliable energy transport system.

An important part in designing the cable system is the capacity of the surrounding soil to act as a heat dissipater, when the power cables increase their temperature as the transfer of energy occurs. Regardless of whether we refer to the situation in which the cables are buried directly or the situation where the cables are installed in protecting pipes, the soil plays an important role when choosing the cable materials, which prevent excessive temperatures and extend the lifespan of the infrastructure. Given that the soil serves as the sole medium for energy dissipation, the manner in which heat is dissipated constitutes a critical property in determining the permissible current levels that can be transmitted through cables without leading to overheating phenomena. This characteristic of soil is quantified through the concept of thermal resistivity.

Silty soils are fine-grained soils, frequently met in Romania, particularly in regions that are favourable for the installation of wind turbines and the development of photovoltaic solar parks. Properties of these soils such as moisture content and porosity significantly influence their thermal resistivity and heat transmission capacity. In most cases, cables are laid within trenches that are subsequently backfilled with compacted silty soils. The optimal compaction parameters of these soils are determined by their mineralogical composition, moisture content, and porosity. Furthermore, the compaction degree has a consequential impact on the operational efficiency of the electrical energy transmission infrastructure.

For this study, thermal conductivity tests were conducted in laboratory, on silty soil samples compacted at their optimum compaction parameters and at 85 and 90% degree of compaction. The optimum compaction parameters were previously determined by means of Proctor test.

The objective of this study is to provide a comparison between the thermal resistivity parameters of silty soils at different compaction states, as well as to ascertain the influence of factors such as moisture content and porosity on the soil's heat dissipation properties. The findings derived from this analysis may yield valuable insights

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for optimizing the design of energy transmission infrastructure.

GEOTECHNICAL DESCRIPTION OF THE SOIL SAMPLES

On the four samples analysed tests were conducted to determine the grain size distribution, the plasticity and the optimal compaction parameters. The grain size distribution was done following the principles of EN ISO 14688:2018 - Identification and classification of soils.

Table 1 *Mass percentage distribution of analysed soil samples*

No.	Clay [%]	Silt [%]	Sand [%]	Gravel [%]
Sample 1	24	72	4	0
Sample 2	20	76	4	0
Sample 3	29	67	4	0
Sample 4	26	70	4	0

As presented in Table 1, the soil samples are similar from the grain size distribution point of view, being characterized as medium plasticity silty clays.

For the purpose of determining the optimal moisture content and the maximum dry density for compaction, as well as for reconstructing soil samples at varying degrees of compaction, the modified Proctor test was employed in accordance with the ASTM D1557-12 standards. Soil compaction was conducted in five distinct layers, utilizing a mechanical energy input of 2.7 J/m^3 for this procedure. Additionally, the thermal resistivity of the soil was assessed at different compaction degrees (85%, 90%, and 100%) to accurately simulate field conditions, where the attainment of a 100% compaction degree may not be feasible along a cable trench.

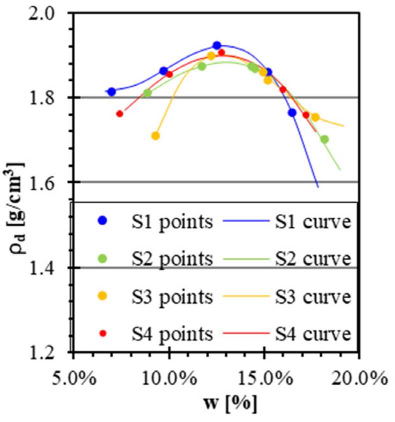

Figure 1 *Modified Proctor test on analysed samples*

Table 2 *Optimal compaction parameters determined using the modified Proctor test*

No.	W_{opt} [%]	$\rho_{d,max}$ [g/m3]
Sample 1	12.90	1.917
Sample 2	13.02	1.883
Sample 3	12.72	1.900
Sample 4	12.79	1.898

THERMAL RESISTIVITY TESTING METHOD

Soil's thermal resistivity was determined by employing the thermal needle probe method.

This method is widely used for measuring the thermal conductivity of soils and deploys a long and thin metallic probe that houses a line heater and a temperature sensor. The method, also referred to as the transient hot wire method, implies that the probe is inserted in the target environment and the line heat source generates heat at a controlled and constant heat flux. Next, the temperature sensor acquires the transient thermal response. This method is widely used because of its convenient practice in fields when measuring for exposed near-surface soils as well as for laboratory measurements (Lee et. al, 2016).

Laboratory testing followed the provisions of the IEEE Guide for Thermal Resistivity Measurements of Soils and Backfill Materials.

Given that the soil was compacted and the moisture content of the samples was low, their consistency was notably high. Consequently, to facilitate the insertion of the measuring probe, three pre-drilled holes were created within the compacted samples. This methodology effectively mitigated any mechanical disturbances that could compromise the structural integrity of the reconstructed samples. Uniform thermal contact along the probe was accomplished through the application of a thermal conductivity paste.

THERMAL RESISTIVITY COMPUTATION

The analytical model used to calculate thermal resistivity was derived assuming a line heat source of infinite length dissipating heat in an infinite medium. Under these conditions, the following equation is valid:

$$\rho = \frac{4\pi(T_2 - T_1)}{q\ln\left(\frac{t_2}{t_1}\right)} \quad (1)$$

Where ρ is the thermal resistivity, T_1 is the temperature measured at some elapsed time interval, T_2 is the temperature measured at another arbitrary elapsed time, q is the heat dissipated per unit length (W/m), t_1 is the elapsed time at which temperature T_1 is recorded and t_2 is the elapsed time at which temperature T_2 is recorded.

A convenient way of determining when the initial transients are over and when the finite boundary begins to effect measurements is to plot temperatures versus the log of time for the duration of test. The data points located on the linear section of the curve can be used to compute the resistivity of the soil.

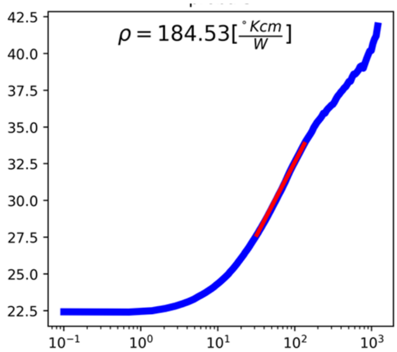

Figure 2 *Processed data resulted from a test conducted on analysed soil samples*

RESULTS AND DISCUSSION

In the graphs plotted in Figure 3 through 9 the results of thermal resistivity tests are presented. The plots represent the variation of the determined parameter with respect to the moisture content of the soil sample. For each analysed sample of certain degree of compaction (or certain dry density) the thermal resistivity was determined for different moisture contents. As it was described in the previous chapters, for each situation the thermal resistivity was obtained by averaging the results of 3 tests.

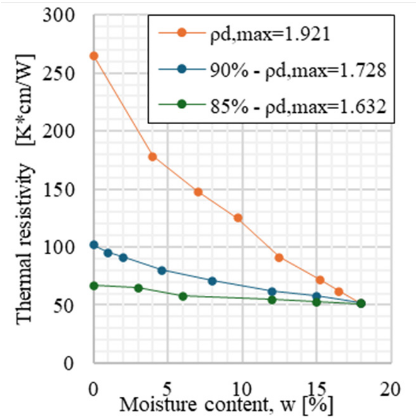

Figure 3 *Plot of the thermal resistivity variation of soil sample 1*

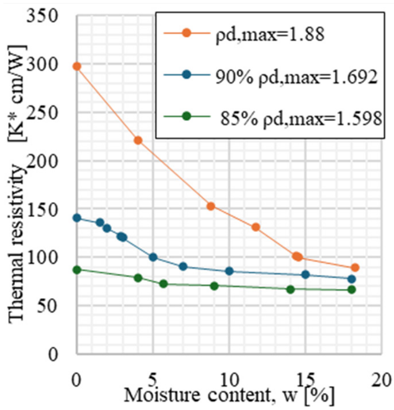

Figure 4 *Plot of the thermal resistivity variation of soil sample 2*

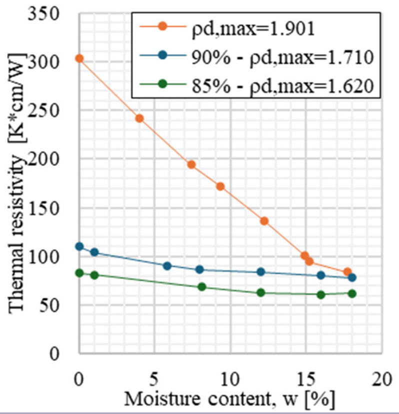

Figure 5 *Plot of the thermal resistivity variation of soil sample 3*

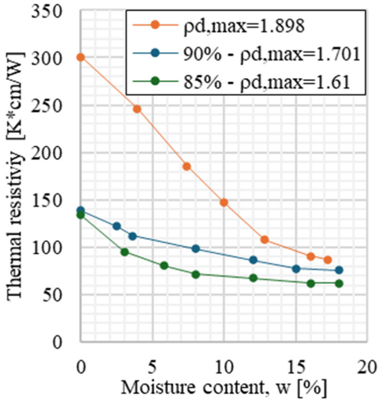

Figure 6 *Plot of the thermal resistivity variation of soil sample 4*

Having determined results for varying degrees of compaction at different moisture contents, dry-out curves for the analysed soil samples were constructed. These representations have significant applicability in real-world design scenarios, as soil moisture content may fluctuate over time, and the degree of compaction achieved in the soil surrounding the cables may diverge from the originally specified design parameters during execution.

The presented graphs underscore the significance of the degree of compaction on thermal resistivity, as the soil's ability to function as a thermal dissipater is markedly diminished when the soil exhibits greater porosity. Moreover, a substantial reduction in the heat transfer capacity was observed with increasing water content in the sample, irrespective of the degree of compaction.

CONCLUSION

The objective of this study was to investigate the thermal resistivity of silty soils across varying moisture contents and degrees of compaction. The aim was to draw conclusions regarding the thermal performance of this material in diverse construction and design contexts.

Through the correlation of the results obtained regarding thermal resistivity and the moisture content of the samples, the analysis highlighted the negative effect that lower level of moisture contents exerts on the heat transfer properties of the soil. This relationship indicates that as moisture content lowers, the ability of the soil to conduct heat effectively diminishes, thereby impacting its thermal performance in practical applications.

Previous studies have stated that the lowest thermal resistivity is obtained at maximum dry density and optimum moisture content (Lodenkemper, 2022; Wang et al., 2024). Additionally, standards for measuring thermal resistivity indicate that as dry density increases, resistivity decreases (IEEE Std 442, 2017). However, in the presented research, the results showed a decrease in thermal resistivity as the dry density of the soil was lowered.

Considering the obtained results, more research is necessary on the influence of the soil structure and porosity on the thermal resistivity of different soils.

In all the examined cases, irrespective of the degree of compaction or the dry density of the material, thermal resistivity exhibited a reduction to a comparable value upon reaching approximately 15% moisture content. This observation suggests that the soil's capacity to function as a heat dissipater does not continue to escalate with increasing moisture levels beyond a specific threshold.

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