Measurement and modeling of thermal conductivity of loess at the location of the Airport "Nikola Tesla" in Surčin

Nikola Božović[a], Marija Krstić[a], Goran Todorović[b], Radovan Gospavić[b], Milica Mirković Marjanović[a], Snežana Ilić[a], Aleksandar Kijanović[a]

[a] *Institut za ispitivanje materijala, Beograd, Srbija*
[b] *Građevinski fakultet, Univerzitet u Beogradu, Srbija*

ABSTRACT

The thermal conductivity of a material is the parameter that is most reliably determined experimentally. The problem of determining the thermal conductivity in the soil is greater because the soil is heterogeneous, so for the same soil this parameter may be different depending on their physical characteristics. Therefore, it is necessary to adopt an appropriate model for describing the thermal conductivity of the soil for a particular location after the necessary tests are performed. This paper is based on experimental measurements of soil thermal conductivity as a function of moisture content in the area of the "Nikola Tesla" Airport construction site in Surčin and the adoption of one of the existing theoretical models that would satisfactorily describe changes in thermal conductivity. Based on the obtained results of experimental research, a two-parameter fitting of the measured values of thermal conductivity of the soil was performed on the Côté-Konrad model, which proved to be reliable and the simplest to describe the thermal properties of loess in the area of Belgrade.

KEYWORDS

Thermal conductivity; Moisture content, Loess.

1. INTRODUCTION

Thermal conductivity is the most important parameter of materials in the field of thermal construction of buildings. Research in the field of thermal conductivity, and finding new materials that would ensure lower energy consumption, is inexhaustible. The thermal conductivity of materials is influenced by very complex physical processes of heat transfer between atoms and molecules, so for liquids and solids this parameter is determined exclusively experimentally.

The need to determine the thermal conductivity of the soil is especially pronounced in the construction of underground systems, primarily cables and pipelines. With low soil thermal conductivity, cables and pipelines can experience overheating and potential combustion. When it comes to underground hot water systems, the surrounding soil needs to be of low thermal conductivity in order to reduce heat losses from the pipes to the ground. Therefore, it is necessary to conduct thermal tests and make the correct choice of backfill material to ensure long-term use of underground systems.

Due to the heterogeneous composition of the soil, a large number of factors affect the size of thermal conductivity, among them the most prominent is soil moisture, followed by granulation, porosity, bulk density. As the moisture content increases, so does the thermal conductivity. Also, the same tendency was observed due to the increase in bulk density, ie due to the decrease in porosity.

The paper presents the dependence of the thermal conductivity of loess on the moisture content obtained experimentally. Loess is a material of dusty-sand structure and as such is suitable for burying installation trenches, especially due to the reduction of dynamic loads dominant in the road infrastructure.

2. EXPERIMENTAL RESEARCH

2.1. Material sampling

A soil sample was collected in the area of the "Nikola Tesla" Airport construction site in Surčin. Sampling was carried out in the pit, from the first horizon of the loess, in one bag with a total weight of 25 kg. The soil sample is disturbed, in a loose state.

The first horizon of the loess consists of monotonous clay - sand dust of light brown color, mostly aggregate microporous, less often and macroporous structures. In the area of "Nikola Tesla" Airport in Surčin, the spread of the first horizon was recorded up to 5 m deep.

The tubular loess structure is partially visible by the occasional appearance of open or macropores filled with clay - dust matrix. In some places, large solitary concretions of carbonates appear, less often powder.

The first horizon of the loess corresponds to the soil of low and medium plasticity. (CL - CI) In a state of natural moisture, the soil is semi - hard and crumbles with less effort. The physical characteristics of the examined loess are shown in Table 1.

Table 1. Physical characteristics of the examined loess

	clay	dust	sand	gravel
Granulation	<0.002	0.002-0.06	0.06-2.00	2.00-60
	20%	74%	6%	0%
Moisture content in natural state	23.20%			
Ateberg	w_l	w_p	I_p	I_c
	38%	21%	17%	90%
Density	γ		γ_s	
	$18 kN/m^3$		$27.6 kN/m^3$	

For measurements of loess thermal conductivity, samples were prepared according to Proctor 's experiment (Figure 1). The soil is compacted by compaction in a cylindrical mold using standardized energy. The volume of the cylinder is 950 cm^3, compaction is done with a hammer weighing 2.5 kg, which falls freely from a height of 30.5 cm. The soil is compacted in three layers with 25 strokes per layer.

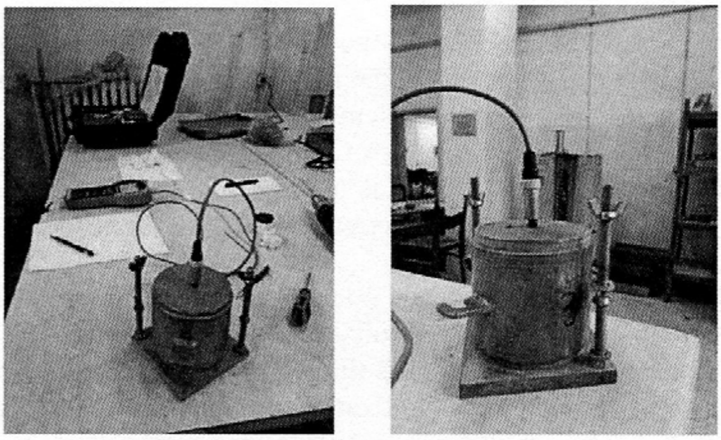

Figure 1. Loess sample prepared in a mould for Proctor's experiment

The thermal conductivity test of the loess was first performed at a natural humidity of 23.2%, after which the sample was dried at a temperature of 105 ° C. The test was performed on a dry sample and for humidity in the amount of 5%, 10%, 15% and 20%.

The loess thermal conductivity test was performed using a TLS100 portable meter (Thermtest Instruments / Thermtest Inc. Canada / Thermtest Europe AB Sweden) (Figure 2) used to measure the thermal conductivity and thermal resistance of various samples, including soil, rocks, concrete and polymers, and can be applied both in the field and in the laboratory. The device consists of a measuring unit and a needle probe. Thermal conductivity is measured with a needle probe that has a large diameter to length ratio to produce conditions for an infinitely long sample. The probe consists of a heating element and a temperature measuring element and is inserted into the sample. Known current and voltage are applied to the probe and an increase in temperature is recorded for a certain period of time. Thermal conductivity was obtained by analyzing the approximately linear part of the quasi-stationary temperature-time response.

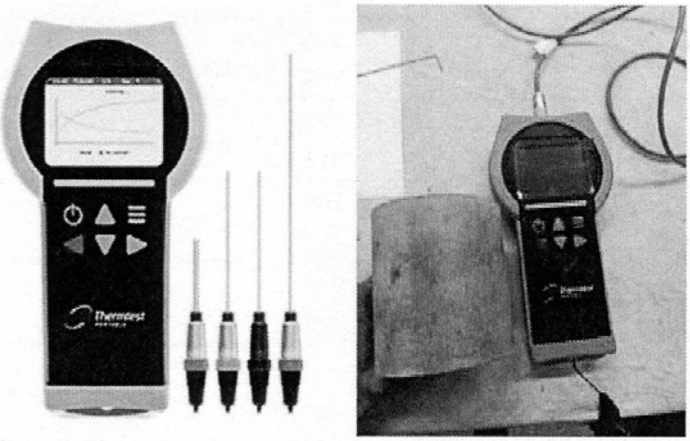

Figure 2.Thermtest apparatus for measuring thermal conductivity

Thermal conductivity is calculated from the linear part of the experimental curve described by the expression (1).

$$\lambda=Q/(4\pi(T_2-T_1))\ \ln(t_2/t_1) \tag{1}$$

where λ is thermal conductivity (W / mK), T_1 temperature measured at any arbitrary elapsed time (K), T_2 temperature measured at any arbitrary elapsed time (K), Q heat flux losed per unit length (W/m), t_1 elapsed time for which the temperature T_1 is recorded , t_2 elapsed time for which the temperature T_2 is recorded .

The characteristics of the measuring device are shown in Table 2.

Tabela 2. Characteristics of the Thermtest measuring device

Measurement capabilities	Bulk Properties
Thermal conductivity	0.1 to 5 W/m•K
Thermal resistivity	0.2 to 10 m•K/W
Measurement time	3 min.
Reproducibility	2%
Accuracy	5%
Temperature range	-40 to 100°C
Minimum sample size	100 mm in length, 50 mm diameter
Largest sample size	Unlimited
Standards	ASTM D5334-14, IEEE 442-1981

Thermal conductivity was tested at four points, two at each base of the cylindrical sample. The mean value of the two most approximate results was adopted as the final value of thermal conductivity for the corresponding humidity. The test results are shown in Table 3.

Table 3. Results of loess thermal conductivity testing

S[%]	γ_d [kN/m^3]	e [%]	λ (W/mK)	λ_s (W/mK)	R (mK/W)	R_s (mK/W)
0%-1	15.59	0.770	0.235	0,234	4.255	4.274
0%-2			0.233		4.292	
5%-1	16.95	0.628	1.246	1,258	0.803	0.795
5%-2			1.270		0.787	
10%-1	17.17	0.607	1.876	1,822	0.533	0.550
10%-2			1.768		0.566	
15%-1	17.74	0.556	1.968	1,941	0.508	0.516
15%-2			1.913		0.523	
20%-1	16.49	0.674	1.764	1,767	0.567	0.566
20%-2			1.770		0.565	
23.2%-1	16.10	0.714	2.026	2,197	0.452	0.456
23.2%-2			2.090		0.459	

3. ANALYSIS OF TEST RESULTS

Soil thermal conductivity is one of the basic parameters for modeling the thermal flux and temperature field in the soil. This parameter depends on the composition of the soil, especially the quartz content, the particle size distribution in the soil, soil temperature, moisture content, dry soil density, porosity and organic matter content.

The test results indicate an increase in thermal conductivity, ie a decrease in thermal resistance with increasing water content in the sample. The test results are also influenced by the bulk density of the sample in the dry state, ie the porosity of the sample. In the dry sample, the contact between soil particles is weaker due to the absence of water and the pores are filled with air whose thermal conductivity is 0.023 W/mK. With a small increase in moisture, the particles come into contact with the aqueous film. As the thermal conductivity of water is 0.58W/mK, the effect of increasing the thermal conductivity of the soil by a small percentage increase in moisture is significant.

Different models of thermal conductivity calculation according to soil types and soil water conditions have been developed in the literature, ie. whether it is frozen ground. One of the most widely used models is the Johansson model [1]. Johansen's model of thermal conductivity of soil gives the expression for thermal conductivity of soil in the form (2):

$$\lambda = \lambda_{dry} + (\lambda_{sat} - \lambda_{dry}) \cdot K_e \tag{2}$$

where λ_{dry}, λ_{sat} and K_e are thermal conductivity of dry soil, soil saturated with moisture and Johnson's weight parameter respectively. K_e is a function of soil moisture content. For porous soils, with a significant content of fine-grained aggregate, such as light soils, the one proposed by J. Côté, J. M. Konrad (3), which is:

$$K_e = \frac{kS}{1 + (k-1)S} \tag{3}$$

where k and S are empirical coefficient and soil moisture content respectively. The empirical coefficient depends on the type of soil.

Table 4 shows the average values of thermal conductivity of loess in Surčin, the first horizon, obtained by measuring according to the standard procedure with a digital measuring device Thermtest.

Table 4. Mean values of thermal conductivity for different moisture content

S [%]	0	5	10	15	20	23.2
λ[W/mK]	0,234	1,258	1,822	1,941	1,767	2,197

Figure 3 graphically shows the measurement values from Table 4 as well as the Côté-Konrad model of loess thermal conductivity obtained by fitting the values of the parameters k and λ_{sat} to the experimental results. The fitting was done by the Least Squeres method. The figure shows that the Côté-Konrad model is a good model for describing the thermal conductivity of loess.

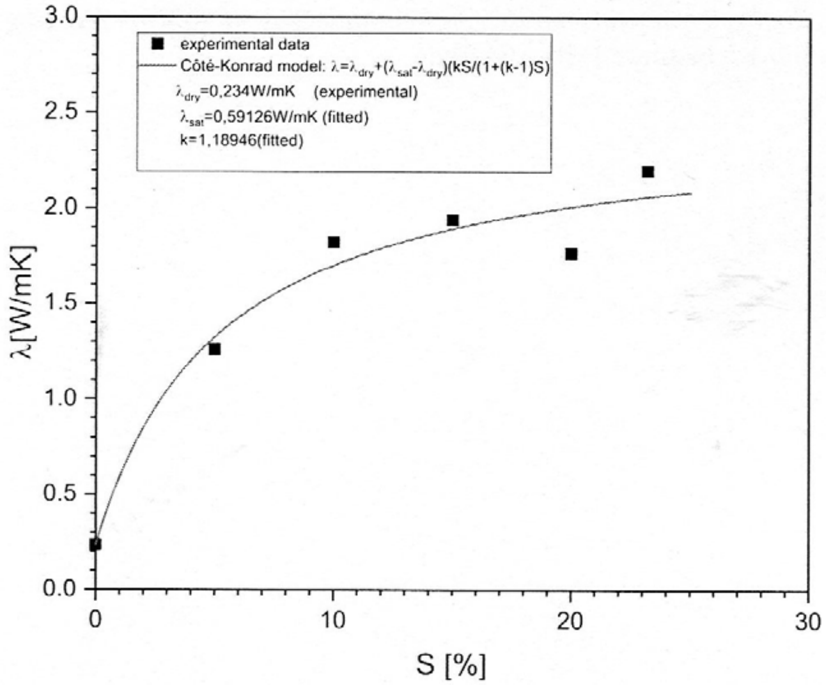

Figure 3. Measured thermal conductivities of loess (black dots) and Côté-Konrad model of thermal conductivity (red line) with fitted values of parameters

4. CONCLUSIONS

The paper presents one of the methodologies of experimental tests of thermal conductivity of soil. A Côté-Konrad analytical model was chosen that favorably describes the dependence of thermal conductivity and water content for the selected soil sample. Based on the experimental test results, a two-parameter fitting of the Least Squares method was performed to determine the required parameters of the Côté-Konrad model.

Results of this research are next:

1. The methodology for experimental research of thermal properties of loess in the area of Surčin has been determined.
2. The thermal conductivity of loess in its natural state has been determined experimentally.
3. An adequate analytical model for thermal calculations of structures in loess in the area of Belgrade is proposed.

can be predicted. One should strive to find a compromise between compaction and the required thermal conductivity of the soil, depending on the purpose of the underground facility. Experimental research before the start of the project can contribute to economy by ensuring energy savings with the choice of adequate parameters and technology of execution.

REFERENCES

[1] O. Johansen, 1977. *Thermal Conductivity of Soils*, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

[2] J. Côté, J. M. Konrad, 2011. *A generalized thermal conductivity model for soils and construction materials*, Canadian Geotechnical Journal 42(2):443-458.

[3] T. Nikiforova, M. Savytskyi, K. Limam, W. Bosschaerts, R. Belarbi, 2013. *Methods and Results of Experimental Reseraches of Thermal Conducivity of Soils*, Energy Procedia 42, 775-783.

[4] M. Fernando Ballesteros Barreto, 2020. *Thermal properties in artificially prepared samples mimicking deep ypresian clays*, Escola de Camins, UPC Barcelona tech.

[5] M. Brekic 2021, *Report on testing the thermal conductivity of soil for Heating Pipeline Project Obrenovac-Novi Beograd*, Institute IMS, Belgrade