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Energy Procedia 42 (2013) 775 – 783

Energy
Procedia

The Mediterranean Green Energy Forum 2013, MGEF-13

Methods and results of experimental researches of thermal conductivity of soils

Tetiana NIKIFOROVA[a]*, Mykola SAVYTSKYI[a], Karim LIMAM[b], Walter BOSSCHAERTS[c], Rafik BELARBI[b]

[a]*SHEE "Pridneprovsk State Academy of Civil Engineering and Architecture", 49600 Dnipropetrovsk (Ukraine)*
[b]*Laboratory of engineering sciences for environment (LaSIE), University of La Rochelle, France*
[c] *Royal Military Academy, Av. de la Renaissance, 30 B – 1000 Brussels*

Abstract

To meet the challenges of earth sheltered and green roof buildings, application of the heat pumps that use the heat of soil it is necessary to have the thermo physical characteristics of the soils. The studies in this field are extremely insufficient.

The purposes of this research are to research the thermo physical characteristics of different soil types and to develop methods for the soils thermal conductivity determination.

The paper sets out the methodology of experimental studies of soils thermal conductivity. The analytical dependence for the heat conductivity coefficient determination for different types (sand, clay and loam) and humidity of soil is obtained. The dependence can be used for thermal-technical calculations of earth sheltered buildings.

Keywords: Thermal, Conductivity, Soil, Experimental, Building, Earth sheltered;

1. The methodology of experimental research

The investigations of soil thermal conductivity were carried out using a mobile measuring thermal conductivity MIT - 1 produced by "Karat" (Chelyabinsk, Russia).

The principle of operation is based on measurement of probe temperature for a certain time when it is heated at a constant rate. Probe should be placed inside the sample to ensure maximum thermal contact with the sample.

Technical characteristics of the device "MIT-1.0" are shown in Table 1.

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* Mykola Savytskyi. Tel.: +38 0562 47 02 98; fax: +38 0562 47 02 98.
E-mail address: sav15@ukr.net.

doi:10.1016/j.egypro.2013.12.034

Table 1. Technical parameters of "MIT-1.0"

Parameters	*Value (range)*
Measuring range conductivity, W/(m·°K)	0,01…2
The margin of error, %	7
Measurement time, min	7
Operating temperature range, °C	-10…+50

Measurement of the materials heat conductivity was accomplished by measuring the density of stationary heat flow according to GOST 30290-94 [1], or the method of determining the thermal conductivity of a cylindrical probe in accordance with GOST 30256-94 [2]. The first method provides a higher accuracy of the measurements, but is associated with certain difficulties of accurate specimens preparation and requires a long period (up to 6 ... 10 hours) to obtain a stationary heat flow.

The device "MIT-1.0" implements the thermal probe with increased accuracy due to the large number of temperature measurements and special mathematical processing of the results.

To determine the thermal conductivity of the samples are made in the form of bars of 65x65x150 mm or a cylinders with a diameter of 50 mm and a length of 150 mm (Fig. 1a). The hole with diameter equal to the probe size is prepared in a specimen or in a product. The probe must fit into the hole without any clearance and closely as possible. Samples of loose or bulk materials are placed in a mold with low thermal conductivity and the same or larger size. To improve the accuracy of measurement, the probe and the prepared hole are smeared with thermal-water paste, grease or petroleum jelly. The samples with an inserted probe are kept at constant temperature for at least two to four hours in dependence on the mass and thermal conductivity of the material.

Soil moisture was determined in accordance to GOST 5180-84 [3], the method of drying up of constant mass (Fig. 1b).

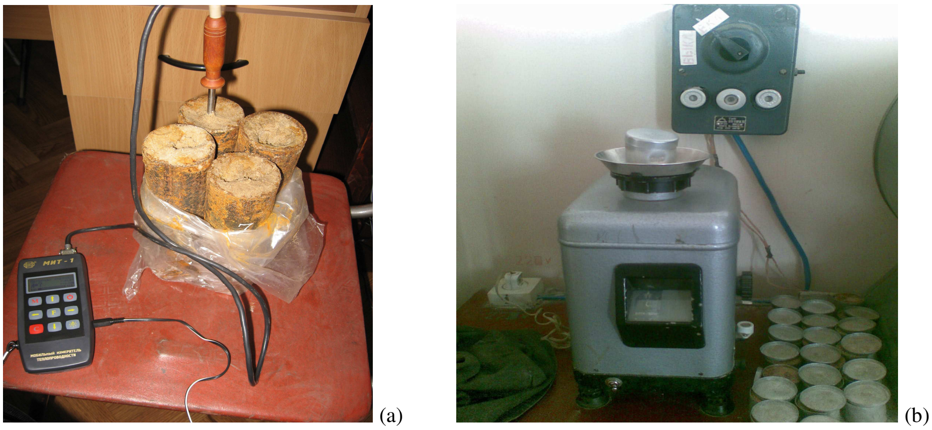


Fig. 1. (a) Measuring of heat conductivity of soil by device "MIT 1"; (b) determination of soil humidity by the method of drying to permanent mass

2. Thermal characteristics of soils

The geology of the territory of Dnipropetrovsk consists of quaternary deposits represented by alluvial-diluvial and alluvial differences underlain by granite Archean-Proterozoic age.

Coverslips (structural) and loess loams are widespread within the city limits. The main part of their particle size distributions are flour fraction. Pale brownish covering clay loams are encountered most often. It is divided into separate uniform particle size with a predominance of silt particles. There are some places with brown clay and clay loam divided into separate parts. Coarse grained rocks is incremented with the depth. These grounds are underlain by sand deposits. Quartz, gray, unequigranular, dense and homogeneity sands are at the base of gravel and crushed crystalline rocks.

On the surface the bedrock is covered with backfill soil and buried topsoil.

The study of the thermal conductivity of soils was conducted in the laboratory. For this ground samples were collected in accordance with the rules of engineering and geological surveys.

The thermal conductivity of soils depending on their moisture was determined for sand, clay loam and clay in the laboratory at different moisture in the frozen state and positive temperature (Tab. 2), as well as in terms of natural occurrence (Tab. 3). According to the Tables 2, 3, dependences characterizing the change of thermal conductivity on density are obtained (Fig. 2, 3). These data were compared with data reported in [4].

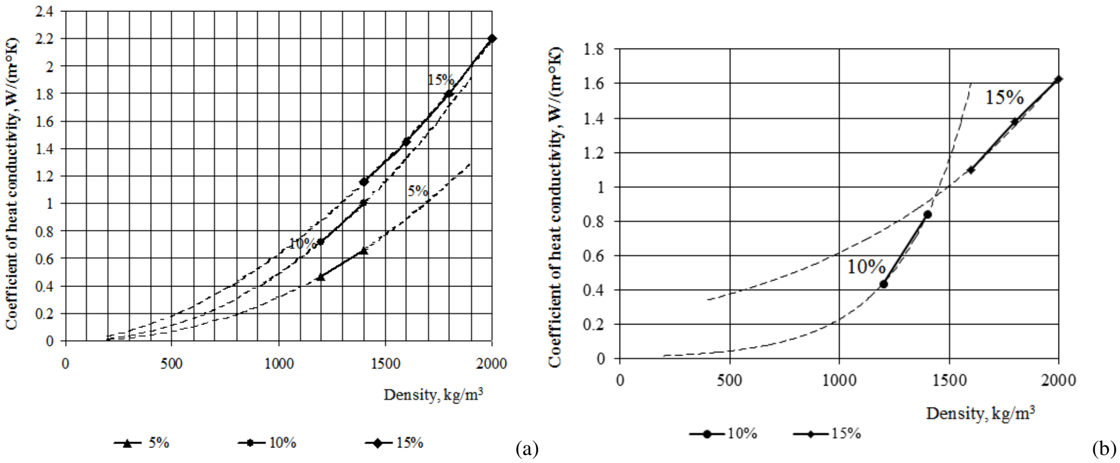
Table 2. Thermal conductivity coefficient of sand, loamy sand and clay for different humidity in laboratory environment

Name of breed	*Humidity, %*	*Density, kg/m*^{3}	*Coefficient of heat conductivity, W/(m·°K)*	
			at a positive temperature	*in the frozen state*
Sand	5	1200	0,47	0,6
	10	1200	0,72	0,92
	5	1400	0,66	0,8
	10	1400	1,0	1,95
	15	1400	1,16	1,57
	15	1600	1,45	1,86
	15	1800	1,8	2,2
	15	2000	2,2	2,56
Loamy sand	10	1200	0,44	0,52
	10	1400	0,84	0,8
	15	1600	1,1	1,28
	15	1800	1,38	1,52
	15	2000	1,63	1,74
Loams and clays	10	1400	0,51	0,79
	15	1400	0,65	0.98
	20	1400	0,76	1,09
	20	1600	1,02	1,3
	20	1800	1,1	1,4
	20	2000	1,44	1,7

Table 3. Thermal conductivity coefficient of natural bedding soils for different humidity

Mountain breed	*Density, kg/ м*^{3}	*Humidity, stakes of unit*	*Coefficient of heat conductivity, W/(m·°K)*
Highly humified loamy sand, with plenty of vegetation and woody debris	1200	0.488	0.972
	1420	0.781	1.070
	1300	0.878	1.040
	1470	0.975	1.020
	1390	1.266	0.729
Loamy sand poorly humified, with a small of vegetable residues	1335	0.292	0.927
	1367	0.325	1.020
	1542	0.495	1.512
	1556	0.508	1.337
	1650	0.6	1.326
Loamy sand	1500-1800	0.081	0.523

		0.114	0.605
		0.132	0.791
		0.150	0.814
		0.180	1.221
		0.185	0.907
		0.200	1.012
		0.235	1.326
Fine-grained sand, silty, poorly humified, with vegetation and woody debris	1542	0.312	1.303
	1620	0.352	1.430
	1750	0.468	1.489
Sand is medium-grained, poorly humified, with a little vegetable residues	1915	0.065	0.806
	2095	0.093	1.157
	2400	0.236	1.745
Sand medium-grained	1622	0.007	0.442
	1663	0.032	0.849
	1780	0.109	1.361
	1803	0.119	1.768
	1835	0.14	1.512
	2015	0.251	1.733
Assorted sand	1500-1800	0	0.023
		0.029	0.072
		0.044	0.686
		0.047	0.605
		0.071	0.663
		0.088	0.814
		0.09	0.837
		0.094	0.896
		0.108	0.884
		0.126	1.233
		0.131	1.291
		0.152	1.140
		0.186	1.337
Loam	1500-1800	0.095	0.395
		0.12	0.547
		0.21	0.675
		0.25	0.768
		0.25	1.012
		0.275	1.303
		0.365	1.861
		0.365	1.745
		0.365	2.059
Loam clay mixed with small quantity of sand particles, humified, with a little vegetable residues	1023	0.331	1.372
	1037	0.347	1.454
	1049	0.35	1.500
	1077	0.399	1.791
	1102	0.433	1.861
	1483	0.929	2.093
	1335	1.514	0.936
Loamy sand - loamy breed with scree, slit the child and fragments of diabase	2080	0.045	0.942
	2130	0.071	0.907
	2135	0.073	1.105
	2205	0.108	1.279
	2250	0.131	1.198
	2250	0.132	1.535
Sand with pebble and hoggin (sand of 40-50% on volume and hoggin 60-50%)	2250	0.005	0.651
	2315	0.034	1.128
	2330	0.042	1.384
	2345	0.048	1.384
	2410	0.077	1.942



(a) (b)

Fig. 2. Dependence of heat conductivity coefficient of the sand (a) and loamy sand (b) on the density of the soil for different humidity

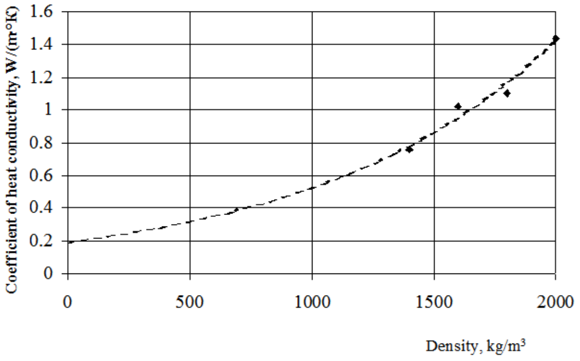


Fig. 3. Dependence of heat conductivity coefficient of loam and clay on the density of soil for humidity of 20%

The curves show that the thermal conductivity of the soil increases with the density increasing. The results confirm the general laws of the materials thermal conductivity. In general, the dependence of the thermal conductivity of the soil density can be described by the empirical equation:

$$\lambda = a \cdot \rho^{b}, \qquad (1)$$

where λ is a thermal conductivity, W/(m·°K);

a, b are coefficients (Tab. 4);

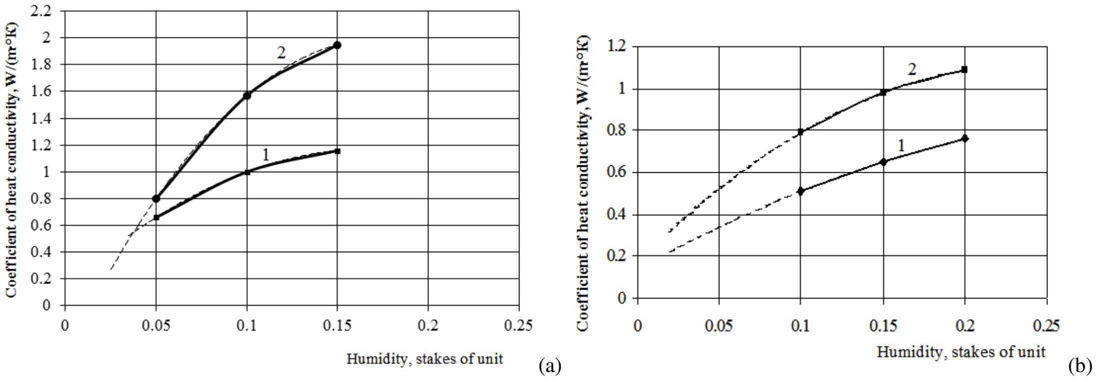
ρ is a density, kg/m^3.

The thermal conductivity of soils (table 2, 3) was obtained by studying the dependence of the thermal conductivity on the soil moisture.

The dependence of the thermal conductivity of sand, loam and clay on the humidity and temperature of the positive temperature and in the frozen state is presented in fig. 4. The diagram of the thermal conductivity coefficient for different types of soil moisture is presented in fig. 5.

Table 4. Values of coefficients (*a, b*) according to the dependence (*1*) for sand, loamy sand, loam and clay

Type of soil	*Humidity, %*	*Value of coefficients*		*Coefficient of correlation*
		a	*b*	
Sand	5	$8 \cdot 10^{-8}$	2,2024	
	10	$2 \cdot 10^{-7}$	2,1311	
	15	$3 \cdot 10^{-6}$	1,7957	0,999
Loamy sand	10	$5 \cdot 10^{-14}$	4,1948	
	15	$2 \cdot 10^{-6}$	1,7656	
Loam and clay	20	$4 \cdot 10^{-6}$	1,6764	0,959



(a) (b)

Fig. 4. Heat conductivity coefficient of sand (a), loam and clay (b) in dependence on humidity: 1 - at a positive temperature; 2 - in the frozen state.

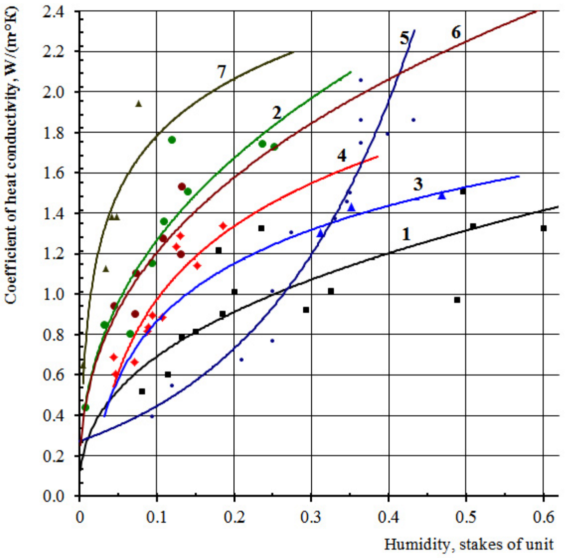


Fig. 5. Heat conductivity coefficient for different soil types: 1 - sandy loam; 2 - medium-grained sand; 3 - silty sand; 4 - assorted sand; 5 – loam; 6 - loamy sand - loamy breed; 7 - sand with pebbles and gravel

3. Analysis of results

From fig. 4, 5, it can be seen that the coefficient heat conductivity values increase with soil moisture increasing upon both positive and negative temperatures.

The investigated types of soils in the dry state have a heat conductivity coefficient of 0,23–0,35W/(m·°K). The increase of thermal conductivity continues to full moisture capacity. Full moisture capacity is equal to W=20% - for sand, W=50-60% - for loamy sand, W=70-80% - for loam.

This is due to poor contact between the particles of dry soil, the pores of which are filled with air (the coefficient of heat conductivity of air is 0,023 W/(m·°K)). The particles begin to touch a water film with humidity increasing (thermal conductivity of water is 0,58 W/(m·°K)). This effect has a significant influence on heat conductivity increase at the initial stage of wetting. The thermal conductivity is maximal if moisture value is almost equal to total moisture capacity. During further increase of moisture, the soil particles dissolve by water. This results in a heat distribution through water. The thermal conductivity influence on the mineral part decreases. The heat conductivity coefficient of the soil decreases at the same time.

The dependence of the heat conductivity coefficient on humidity confirms the general dependencies described in [5, 6].

As can be seen from fig. 5, the dependence of heat conductivity coefficient on moisture content has a different character for fine and coarse rock. Heat conductivity coefficient increases slowly for loam. It is 1,0 W/(m·°K) when a maximum molecular moisture capacity is W=27%. Then the heat conductivity coefficient increases rapidly and at humidity of W=40% it is equal to 1,95 W/(m·°K). The heat conductivity coefficient of sand is growing rapidly during the early stages of hydration. At 15% moisture the increase the thermal conductivity of sand slows down (Fig. 5, curve 4). If W=15% its thermal conductivity is equal to 1,2 W/(m·°K); if W=20% - 1,35 W/(m·°K). The heat conductivity coefficient of loam increases approximately linear - from 0,25 W/(m·°K) in a dry state to 1,2W/(m·°K) if humidity W=40%.

Fig. 5 shows that the thermal conductivity of coarse rock (curves 2, 4, 6, 7) is higher than the thermal conductivity of fine rocks (curves 1, 3, 5) at same humidity values. The curves have positive curvature for loamy sand and sand, whereas for the loam - negative. The values of the thermal conductivity for the same types of soil are not uniform distributed due to non-uniformity of ground.

The behaviour of the curves is due to the fact that fine rocks have many small mineral particles. These particles have many contacts. Thermal conductivity in contacts is very low. In sandy rock particles are larger and have less contact in the same volume because of larger particle size. Most of the thermal resistance of a material accounts for the material particles with high thermal conductivity.

In the initial stages of moistening, rock particles are enveloped by a thin water shell. The contacts between the particles are still poor and continue to be the heat passage. Since the specific surface of fine breeds more than of the coarse, more moisture is required to clothe the fine particles with rock aqueous film.

After filling the interstices between the particles with water, the heat is transferred through the particles and the highly conductive water "bridges". Therefore, the heat conductivity of loam is lower than of sand at the same moisture contents (up to the maximum capacity).

The curves show that at the same moisture the heat conductivity coefficient increases from rocks with plenty of vegetation residues and very humus to the rocks with little humus and fewerof vegetation. The thermal conductivity of rocks rises from fine to coarse rocks (Fig. 5).

The empirical dependences of thermal conductivity for types and moisture values of soils were determined by approximation of the obtained heat conductivity values.

The dependence for sand is:

$$\lambda = a \cdot W + c; \qquad (2)$$

for clay is:

$$\lambda = a \cdot e^{cW}; \tag{3}$$

for loam is:

$$\lambda = a_1 \cdot W^2 - a_2 \cdot W + c, \tag{4}$$

where λ is a heat conductivity coefficient of soil ($W/m \cdot °K$);
W is a humidity of the storage unit;
e is the base of the natural logarithm;
a, c are the coefficients.

The coefficients (a, c) in the formulae (*2, 3, 4*) changed in dependent on the grain-size distribution, the amount of vegetable residues and the degree of soil humus.

Table 5 presents the values of the coefficients (a, c) for the studied types of soil and the number of curves which include the coefficients.

Table 5. Values of the coefficients according to equations *2, 3, 4* for the studied soil type

Type of soil	*Value of the coefficients*		*Equation*	*Number of curve, fig. 5*
	a	*c*		
Silty sand	0.4131	1.816	2	3
Medium-grained sand	0.3932	2.2532		2
Assorted sand	0.5246	2.1804		4
Sand with pebbles and gravel	0.4079	2.7215		7
Loamy sand	1.7346	0.3996	3	1
Loamy sand - loam rocks	2.9433	0.3877		6
Loam and clay	0.273	4.925	4	5

Obtained heat conductivity coefficients for different soil types can be used for thermal-technical calculations of earth sheltered buildings. Also these formulae are confirmed with the previous studies.

4. Conclusions

The paper sets out the methodology of experimental studies of soils thermal conductivity. The analytical dependence for the heat conductivity coefficient determination for different types (sand, clay and loam) and humidity of soil was obtained. The dependence can be used for thermal-technical calculations of earth sheltered buildings. Different results were obtained with this approach:

1. The methodology of thermal characteristics experimental studies (thermal conductivity) of soil (sand, clay and loam) in the Pridneprovsk region was developed.
2. Experimental data on the thermal conductivity of soil in the natural ground state were obtained.
3. The regression equations for the coefficient heat conductivity as a function of soil moisture were developed.

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