Thermal diffusivity of artificial soils at the Moscow State University Soil Station

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Abstract. This study presents the thermal diffusivity vs. water content curves for topsoil, peat, sand and their mixture used to construct the artificial layered soils at the Moscow State University Soil Station. The thermal diffusivity of studied samples varied in a wide range between $9.2 \times 10^{-8}$ m$^2$ s$^{-1}$ for air-dry peat and $9.6 \times 10^{-7}$ m$^2$ s$^{-1}$ for wet sand. The smallest values of thermal diffusivity were obtained for peat, the greatest ones – for sand, and the topsoil demonstrated medium values of thermal diffusivity.

1. Introduction
Nowadays the increase of the urban population and the intensive urban development lead to a rapid urbanization process, during which urban soils are formed under the influence of different anthropogenic factors.

One of the subgroups of urban soils includes man-made soils – artificial soil grounds, purposefully constructed to mimic the natural soil. The man-made soil profile consists of a series of soil layers of different origin and texture and the fertile upper humified layer [1].

At the experimental sites of the Moscow State University Soil Station a model experiment was started in 2011 to investigate such artificial soil profiles consisting of urban soil top layer, sand and sedimentary peat [2]. Since then research was conducted to investigate the peculiarities of self-organization and functioning of man-made soils in Moscow city. The aim of our study was to investigate the thermal diffusivity of different layers of these soils.

Thermal diffusivity is one of the main soil thermal properties, affecting many physical, chemical and biological processes [3]. Thermal diffusivity ($\kappa$) is a derivative characteristic being determined not only by soil thermal conductivity ($\lambda$), but also by soil volumetric heat capacity ($c_v$) [4]:

$$\kappa = \frac{\lambda}{c_v} \quad (1)$$

Thermal diffusivity characterizes soil ability to increase its temperature when being heated and to decrease its temperature due to energy losses at night or in winter. It is highly dependent on soil moisture which makes it necessary to study soil thermal diffusivity across the whole range of soil moisture contents.

Currently, the investigation of peat-sand mixtures is an urgent problem, since these mixtures are widely used in creating artificial soils, urban gardening, green housing and landscape design. Peat thermal diffusivity is rather low [5]. As a result, deep layers of peat soil are poorly heated, and the
upper ones, on the contrary, experience overheating, which can lead to spontaneous combustion. Adding sand to peat increases the thermal diffusivity of mixture as compared to that of pure peat [5]. So, sand additions result in the increase of heat flux into deep soil layers which prevents overheating of upper layers and slows down the mineralization rates of soil organic matter.

The addition of organic matter into mineral soils is often used to increase soil water holding capacity which is favorable for plant growth [6]. On the other hand, as reported in [7], adding sand to peat resulted in the increase in the amount of macropores from 42 to 70% and a decrease in the amount of micropores from 49 to 24%, which made soil water more accessible for plants. During investigations of water-air properties in peat, sand and their mixtures it was found out that the addition up to 60% of sand to peat did not cause significant changes in porosity and pore size distribution. The greatest changes in the porosity and pore size distribution were observed in the range of 0.1–23% of the organic matter content in the material [8].

2. Material and methods
The objects of our research were the horizons of the layered artificial soil at one of the experimental plots at the Moscow State University Soil Station. This soil was constructed in 2012 to study the short-term changes in the properties of man-made soils during exploitation in the city. Soil profile included topsoil layer (0–6 cm), sedimentary peat layer (6–12 cm) and river sand layer (12–18 cm) underlain by 12 cm of cultivated topsoil from the adjacent territory of the Moscow State University Soil Station [2]. We also studied the mixture of these three components prepared in a topsoil:peat:sand ratio of 1.5:1:1.92 by dry weight to mimic the upper layer at another experimental plot also constructed in 2012. Samples were ground in a porcelain mortar with a rubber tip pestle, sieved through a 1 mm sieve and placed into a thin-walled metal cylinder 10 cm high and 3.8 cm in diameter with the same bulk density as in the field (table 1). Each sample was prepared in triplicate.

| Table 1. Properties of topsoil, peat, sand and topsoil-peat-sand samples. |
|-------------------------------------------------------------|
| Bulk density (kg m⁻³) | C (%) | Sand (%) | Silt (%) | Clay (%) |
| Topsoil | 1200 | 2.7 | 30 | 44 | 26 |
| Peat | 310 | 38.5 | – | – | – |
| Sand | 1630 | 0.2 | 94 | 3 | 3 |
| Mixture | 1380 | 9.7 | – | – | – |

Thermal diffusivity of studied materials was determined in the laboratory using the unsteady-state method based on the experimental study of heating dynamics of a soil sample placed into a medium with a constant temperature [9]. At the beginning of the experiment, the studied materials were capillary-moistened with water, and the thermal diffusivity of capillary-moistened samples was measured. Then the samples were dried step-by-step and the thermal diffusivities at different moisture contents were also measured. For each sample, a series of measurements was carried out and finally the water content– thermal diffusivity dependence for the whole range from capillary saturation to the air-dry state was obtained.

3. Results and discussion
The obtained water content – thermal diffusivity dependencies for studied materials are presented in figure 1. It is clearly seen that the experimental curves obtained for different materials differ both in amplitude and shape. The lowest values of thermal diffusivity were obtained for peat material, the greatest ones for sand, and the intermediate ones for the topsoil. Thermal diffusivity of topsoil-peat-sand mixture was quite close to that of pure sand.
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Thermal diffusivity (10^-7 m^2 s^-1)
Water content (m^3 m^-3)

Figure 1. Water content – thermal diffusivity dependencies for topsoil, peat, sand and topsoil-peat-sand mixture.

The values of topsoil thermal diffusivity ranged from 1×10^-7 to 4×10^-7 m^2 s^-1. These values fit into the range of thermal diffusivities obtained for sod-podzolic soils at the Moscow State University Soil Station (2.1–4.3×10^-7 m^2 s^-1) [10]. The water content – thermal diffusivity dependency was an S-shaped curve with a long plateau within the range of low water contents which is not typical for soil monoliths and is quite typical for disturbed samples. This long plateau with practically constant values of thermal diffusivity at quite different moisture contents from 0.02 to 0.20 m^3 m^-3 can be explained by the reduced convective heat transfer with moisture movement due to lowered pore connectivity in the disturbed sample. As a result, the growth of thermal conductivity with soil moisture is rather weak and comparable with that of heat capacity; the resulting thermal diffusivity doesn’t change.

Minimum values of thermal diffusivity were obtained for samples of peat soil; they did not exceed 1–2×10^-7 m^2 s^-1 and practically did not change with a decrease in moisture. Such low values of thermal diffusivity can be related to the high content of organic matter, which has low thermal conductivity and high heat capacity. Besides, the bulk density of peat samples was extremely low (table 1) which can also contribute to the reduction of heat transfer through studied material, hence lowering its thermal diffusivity. Our results are in good agreement with previous studies on the same topic. For example, it was reported in a paper on thermal properties of materials with high water content, that thermal diffusivity of sedimentary peat is lower than that of sand and soil, and reaches 1.5×10^-7 m^2 s^-1 [11]. Similar low values of thermal diffusivity were obtained when studying the thermal regime of marsh peat – up to 1.57×10^-7 m^2 s^-1 [12]. In the same paper [12] it is also argued that the thermal diffusivity of peat varies quite slightly with changes in water contents.

On the contrary, one can see in figure 1 that thermal diffusivity of sandy samples was maximal and reached 9.6×10^-7 m^2 s^-1, which is close to values reported in [13]. This may be explained by rather big size of sand particles and rather high bulk density of the studied material, both enhancing the conductive heat transfer. We assume that the absence of organic matter in sandy samples also played
important role, being the reason of the diminishment of the volumetric heat capacity and also providing good contacts without any heat-insulating films between mineral particles.

It is common knowledge that sand is widely used to improve physical properties of topsoil layer, particularly to enhance the thermal diffusivity of cultivated peat soils which is highly sensitive to sand percentage in the mixture. For example, the addition of 20% of sand (in volumetric terms) to the arable horizon of peaty cultivated soil resulted in an increase in the thermal diffusivity of the material more than twofold – from $0.6 \times 10^{-7}$ m$^2$/s$^1$ to $1.3 \times 10^{-7}$ m$^2$/s$^1$ [5]. When 30% of the sample volume was filled with quartz material, it resulted in thermal diffusivity reaching $1.7 \times 10^{-7}$ m$^2$/s$^1$, which was greater than the initial value obtained for pure peat by more than three times [5]. Sand is also used in mixtures for cultivating plants which prefer well-drained soils. According to the US Golf Association, the percentage of coarse and medium sand fractions in soil should be at least 60%, which makes it possible to lower the degree of compaction of root layer and ensure good drainage [14]. And when studying the impact of artificial fertilizers on the growth and development of Centella asiatica L., researchers also used a soil mixture with a predominance of sand as a substrate, since this plant grows on a well-drained sandy soil [15].

In our study, mixing ratio was close to that recommended in the literature (sand-peat-topsoil in ratio 2:1:1, respectively) [16]. In this case, the thermal diffusivity is almost not reduced compared with thermal diffusivity of sand. More or less similar mixing ratios are also used when conducting various vegetation experiments. For example, to carry out genetic analysis, Lolium perenne L. was placed in a soil mixture containing 3 parts of soil, 1 part of peat and 1 part of sand by volume [17]. During the study of conifer seedlings susceptibility to ozone, these seedlings were planted in a mixture with a similar ratio [18]. During the studies of turfgrass cultivation it was shown that sand-soil-peat mixtures with sand weight ratio of 87% and more provided infiltration rates of 2.3 cm h$^{-1}$ or greater and air-filled porosities of 10% or greater and air-filled porosities of 10% or greater and air-filled porosities of 10% or greater at –30 mbar water retention. In the same study, sand-soil-peat mixtures with 87% of sand gave as good turfgrass growth as those with greater amounts of sand. Lower sand contents resulted in poorer grass yields, low infiltration rates and low drainable porosities [19]. Also, optimum physical characteristics were obtained for mixture containing 5% of soil, 85% of sand, and 10% of peat moss by volume used for golf green construction [20].

4. Conclusion
The natural materials and their mixture used to construct the artificial man-made soils at the experimental plots of the Moscow State University Soil Station differ greatly in basic soil properties, such as bulk density, sand content and organic carbon content. These differences result in significant differences between the water content – thermal diffusivity dependencies obtained for topsoil, sand, peat and topsoil-peat-sand mixture. The smallest thermal diffusivity values were obtained for peat material, the greatest ones for sand, and the intermediate ones for the topsoil. Thermal diffusivity of topsoil-peat-sand mixture was quite close to that of pure sand, though the weight ratio of sand in this mixture was less than 45%.

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