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Structural-functional concept of thermophysical condition of the soils of Altai Region

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Abstract

The goal of this study was to reveal the quantitative interrelations between the thermophysical indices (thermal conductivity and thermal diffusivity) and physical soil properties such as; moisture content, density and detachability. According to the research targets, the soil samples including different genesis and soil particle size distribution were taken in different soil and climatic zones of the Altai Region. These were the sod-podzolic sandy loam soils of the dry steppes, chernozems and chestnut soils of light and medium loamy particle size distribution of temperately arid zone, and the heavy loamy gray forest soils and clayey chernozems of the Altai foothills and low mountains. The samples of undisturbed structures in different soil horizons were studied. To measure the thermophysical properties in laboratory setting, a pulse method of a two-dimensional heat source was used. The method takes into account the patterns of temperature field equalization in an unbounded medium after the heat source termination. A feature of this process is the occurrence of peak temperature at the investigated point of the medium at a given instant. The knowledge of this temperature and time enables to determine the soil thermal capacity, thermal conductivity and thermal diffusivity.

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Introduction

The thermophysical indices of soil such as; volumetric and specific thermal capacities, thermal conductivity and thermal diffusivity in a complex way depend on the variety of soil-physical factors suh as; temperature, density of soil profile structure, the degree of moistening of genetic horizons, particle-size composition, and the organic matter content (Gülser and Ekberli, 2004; Ekberli, 2006; Mikayilov and Shein, 2010; Arkhangelskaya, 2014).

It is known that soil moistening plays the determining role in the formation of the thermophysical condition of soil profiles. In that connection a number of authors (Nerpin and Chudnovskiy, 1970; Makarychev and Mazirov, 1996) stated that in the pattern of the soil thermal indices change depending on the moisture content the following regularities are clearly expressed: volumetric thermal capacity grows in linear fashion with the moisture content increase, thermal diffusivity has a clearly defined maximum at certain moisture content values, and soil thermal conductivity increases nonlinearly tending to "saturation". The density and dispersion of genetic horizons render varied effect on the values of thermophysical factors and on their distribution in soil profile. The study of those interrelations enabled the development of structural-functional concept of thermophysical condition of soils of various genesis.

The goal of this study was to reveal the quantitative interrelations between the thermophysical indices (thermal conductivity and thermal diffusivity) and physical soil properties such as; moisture content, density and detachability.

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Material and Methods

According to the research targets, the soil samples including different genesis and soil particle size distribution were taken in different soil and climatic zones of the Altai Region. These were the sod-podzolic sandy loam soils of the dry steppes, chernozems and chestnut soils of light and medium loamy particle size distribution of temperately arid zone, and the heavy loamy gray forest soils and clayey chernozems of the Altai foothills and low mountains (Makarychev and Mazirov, 1996; Bolotov and Makarychev, 2015). The samples of undisturbed structures in different soil horizons were studied.

To measure the thermophysical properties in laboratory setting, a pulse method of a two-dimensional heat source was used. The method takes into account the patterns of temperature field equalization in an unbounded medium after the heat source termination. A feature of this process is the occurrence of peak temperature at the investigated point of the medium at a given instant (Chudnovskiy, 1976). The knowledge of this temperature and time enables to determine the soil thermal capacity, thermal conductivity and thermal diffusivity. A cylindrical probe was used in the field (Makarychev and Mazirov, 1996).

Results and Discussion

It is known (Makarychev and Mazirov, 1996) that the temperature factor of soil volumetric thermal capacity depends on soil moisture content ($\beta = f(U)$) and changes according to complex law (Figure 1). It grows slowly at low moisture content values, and only in the range from maximum hygroscopic content (MHC) to capillary bond breaking moisture (CBB) its values increase dramatically, and then slow down again.

It should be noted that the soils of different dispersion have an equal temperature factor in dry conditions and at total moisture capacity. Therefore, the clearly defined change of soil temperature factor at soil's intermediate moistening is determined by the cumulative change of the physical conditions of heat transfer in the soil related to water filling the pore space, together with the change of the energy state, properties and behavior of soil moisture.

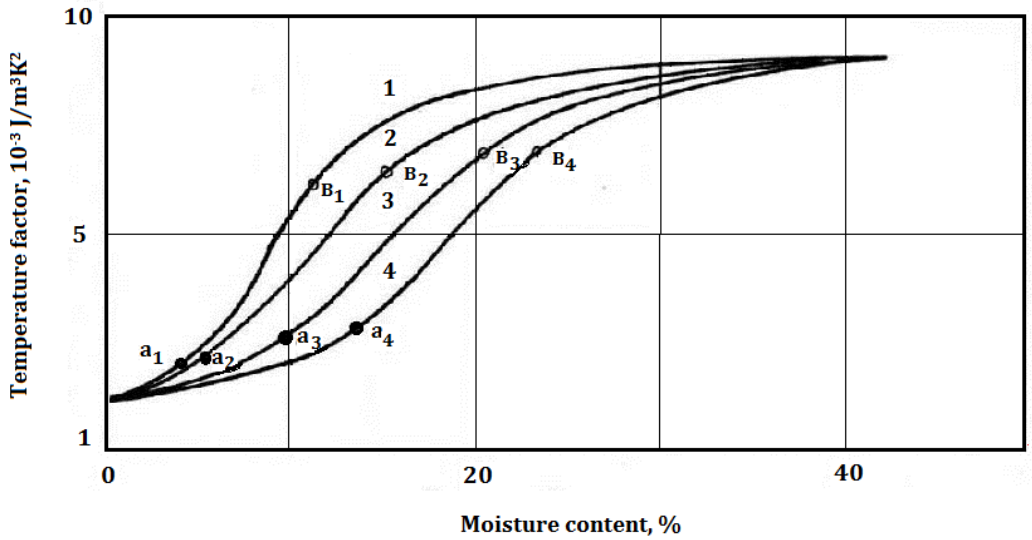

Figure 1. Temperature factor dependence of the volumetric thermal capacity of silica sand (1), sandy loam (2), loam (3) and clay (4) depending on moisture content

At the same time, with the increase of soil moisture content, the thermal diffusivity increases dramatically, reaching its maximum in medium loamy chernozem at the moisture content close to capillary bond breaking moisture. The further moistening results in the decrease of thermal diffusivity.

It is caused by the fact that in soils of different dispersion the most favourable conditions for soil air diffusion and, consequently, diffusive transfer of vapour and heat, are created at various hydrological constants when soil air is completely saturated with water vapour, and aeriferous soil pores have not been separated yet by water slugs. The further increase of soil moisture content results in water filling some of medium-sized and then large pores, and that breaks the connectivity of aeriferous pores system, and reduces the vapour permeability and thermal diffusivity of soil (Panfilov et al., 1982).

Moistening also involves the growth of thermal conductivity to some maximum value. Such run of the curves is explained by moisture gradually forcing poorly heat-conducting air out of soil pores and increasing soil thermal conductivity.

However, according to our data, dramatic increase of soil thermal conductivity clearly defined on the curves is strongly slowed down at this or that hydro-constant owing to swelling processes. As the result the contacts between solid soil particles weaken, and in the system of water-filled pores there are water-free closed pores, and that taken together results in slowing down the rate of soil thermal conductivity increase.

We also revealed quite well-defined reduction of soil thermal diffusivity with increase of soil density. At the same time the volumetric thermal capacity of dry and moistened chernozem increases linearly, and the factor of thermal diffusivity decreases exponentially. We explain those results on the basis of the concept of molecular heat transfer in disperse media and solid bodies. As it is known, gases have high thermal diffusivity. It equals 0.16×10^{-4} m/s for air, 0.13×10^{-6} m/s for water, and still less for solid bodies (Kay and Laby, 1995). Therefore, soil thermal diffusivity would strongly depend on soil compaction, soil particle-size distribution, and the degree of their air or water filled pore space.

Increasing density causes the reduction of air phase volume in soil, and the approach of the solid particles of soil skeleton. Alongside with that the total soil porosity decreases, there are fewer large and more of blind pores, in which the pressure of jammed air is higher than the atmospheric pressure.

Alltogether that causes the growth of air molecules' concentration in the pore space of soil, and the reduction of free-path length of those molecules. At constant temperature the rate of air molecule motion is constant, and the factor of thermal diffusivity is the function of free-path length only. Therefore, with soil compaction, accompanied by the change of pore space structure towards the reduction of air pores sizes, the increase of closed pores number, and the increase of molecule concentration of air contained in the pores, and, consequently, decrease of free-path length of gas molecules, soil thermal diffusivity decreases. In turn, the cumulative change of soil thermal capacity and thermal diffusivity determines the dynamics of soil thermal conductivity. It grows nonlinearly with the increase of soil structure density.

It is quite difficult to reveal the mechanism of the effect of soil particles' dispersion degree on soil thermophysical factors in their natural composition. The cumulative action of large number of factors (structure density, temperature, moisture content, etc.) enable making quality evaluation of the interrelation of thermal indices and particle-size composition only.

The dispersion degree of the horizons affects the factors of soil thermal conductivity and thermal diffusivity in a different way. So, the high content of clay and clay fraction causes the minimum values of thermal transfer factors in soil. The reason of the considered changes, in our opinion, is that the increase of dispersion involves the growth of particles number of soil solid phase, and consequently the number of aeriferous pores, but number of smaller sizes, and also the number of thermal contacts. Altogether it interferes with effective thermal exchange in soil.

Along with the considered factors, organic matter content in soil also renders significant effect on thermophysical factors. That effect is caused by the differences in thermophysical indices of both some granulometric fractions, and organic matter, as peat, for example. So, the specific thermal capacity of silica sand amounts to 821 J / (kg K), clay – 976 J / (kg K), and peat as much as 2000 J / (kg K). At the same time the thermal conductivity of silica sand amounts to 0.35 W / (m K), and peat – 0.11 W / (m K).

The experimental data shows that increasing organic matter content naturally increases both volumetric, and specific thermal capacity. But the thermal transfer factors decrease in that case. At the same time, the thermal transfer factors in the horizons with higher organic matter are considerably lower than in low humus horizons (Table 1).

Table 1. Thermophysical characteristics of some genetic horizons of chernozems with different humus content.

Horizon	Bulk Density, kg/m^3	Humus, %	Heat capacity		Thermal diffusivity, m^2/s	Thermal conductivity, W / (m K)
			Volumetric 10^{-6}, J / (m^3 K)	Specific, J / (kg K)		
A	1330	6.8	1.451	1091	0.220	0.319
AB	1380	4.9	1.501	1088	0.239	0.358
BC	1320	2.6	1.292	979	0.388	0.501

The knowledge of the interrelations of the complex of thermal and soil-physical factors enabled the development of structural-functional concept of thermophysical condition of soils.

Indeed, the thermophysical indices of the genetic horizons of a soil profile are structural-functional indices; this or that pattern of construction of aggregate-structural level of soil organization of elementary soil particles predetermines the amount and degree of variability of thermal capacity, thermal conductivity and thermal diffusivity not only of a specific horizon (horizon structural level), but also of the whole soil profile (level of a soil individual). Thus, the level hierarchy of soil structural organization is sustained (Voronin, 1984).

The structural-functional concept of thermophysical condition of soils is based on the established dependence of the thermal diffusivity maximum and the critical value of thermal conductivity of the function *a(U)* and *λ=f(U)* on the compaction degree of the soils of different particle-size composition.

It is known that the maximum of thermal diffusivity factor of loamy soils is observed at the moisture content close to capillary bond breaking moisture which is characterized by the transition of film-joint moisture into film-capillary moisture.

The moisture potential in that condition is named the potential at the maximum molecular soil moisture capacity (Voronin, 1984). At that potential the superficial forces in isothermal conditions keep the maximum amount of film moisture, and that is explained by two oppositely acting factors – the increase of the thickness and reduction of the area of the films. Thus, the thermodynamic balance between the film and capillary moisture is realized there, determined by the structure of the soil body, when not only the condition of soil capillary bond breakage develops, but also the condition of restoration of diffusive bond in the soil pore space.

In sandy loams the maximum of thermal diffusivity and the critical value of thermal conductivity are linked to the field moisture capacity (FC). Large and medium-sized pores prevail there amounting to 70% of the total porosity; that causes the discrete condition of soil moisture throughout the whole interval of natural moistening of soil. At field moisture capacity in the pores only 40-45% of pore space is water filled, while large pores and some medium-sized pores are air filled (Table 2).

Table 2. Amount of moistened pores (nominator) and air-bearing pores (denominator) in soils at FC and CBB levels, %

Soil texture	at FC		at FC	
	against total porosity	against soil volume	against total porosity	against soil volume
Medium loamy	61/39	32/21	44/56	23/30
Loamy-sandy	45/55	19/23	33/67	14/28

CBB corresponds to: a)70% FC in medium loams
b)FC in loamy sands

In those soils capillary-meniscus and capillary-film moisture movement is expressed very poorly. At the same time, at field moisture capacity the soil moisture acquires the property of capillary bonded water body revealing quite high values of contact thermal conductivity and thermal diffusivity, while the remaining free air pores support considerable thermal and vapour transfer.

In loamy soils where small pores prevail, such hydrological constant as the capillary bond breaking moisture is not expressed, and therefore, the maximum thermal diffusivity values are displaced towards the wilting moisture. At such degree of soil moistening the portion of the capillary-suspended moisture is insignificant and practically all of is presented by the osmotic form, staying in that form in unstable thermodynamic balance.

It should be noted that in the soils of various dispersion degree the change of external or internal conditions should cause the disturbance of the balance and result in the shift of thermal diffusivity maximum and the critical value of thermal conductivity relative to the degree of soil moisture content.

So, at soil compaction accompanied by destruction of large pores, the moisture transition into smaller pores is observed, where the critical potential ψ of maximum molecular soil moisture capacity is observed at lower moisture content, therefore some part of soil moisture moves into the category of capillary-suspended, capillary-supported or gravitational moisture. In that case the air-bonded condition of pore space is destructed and, as consequence, the thermal diffusivity decreases. To restore the balance some part of soil moisture should be removed.

We derived the dependences of moisture content corresponding to thermal diffusivity maximum $Ua_m=f(BD)$ for the soils of clayey (1), loamy (2) and sandy (3) particle-size composition (Figure 2). According to the dependences, the equations of linear regression are derived at the temperature of 20°C:

$$Ua_m(1) = 42.3 - 0.017BD,$$

$$Ua_m(2) = 37.9 - 0.017BD,$$

$$Ua_m(3) = 34.7 - 0.017BD,$$

where, Ua_m – soil moisture content, % of the weight; BD – soil bulk density, kg/m^3.

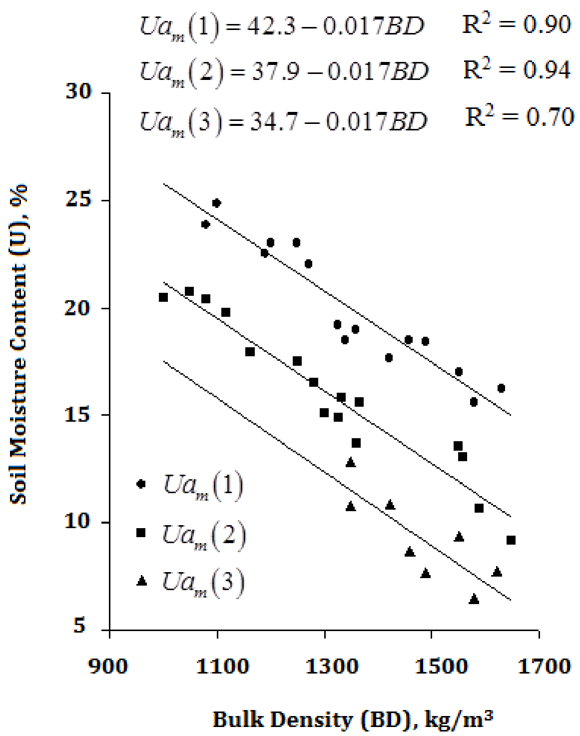

Figure 2. The moisture content corresponding to the maximum thermal diffusivity values of the soils of clayey (I), loamy (II) and sandy loam (III) particle size distribution depending on the bulk density.

The equations for clayey and loamy soils are true within the limits of 900-1600 kg/m^3, and for sandy soils – 1300-1700 kg/m^3. The relation between the composition (mechanical particles) and thermophysical indices is reflected by the equation:

$$Ua_m = -8.9 + 7.2\ln(D),$$

where D – dispersion or the number of particles less than 0.01 mm.

In that case the determination index of curvilinear correlation appears to equal 0.92 at one percent significance level, i.e., to 92% the maximum thermal diffusivity is provided by soil dispersion. The greatest rate of moisture content change, which corresponds to the maximum of thermal diffusivity, is observed in sandy soils. It is slightly less in loamy soils, and in clayey soils it decreases and tends to some limit close to 24% of soil weight (Figure 3).

Figure 3 presents the data of the dependence of the moisture change rate (moisture mobility) at which the extreme thermal diffusivity value depending on the degree of soil dispersion is observed. According to the data of the Figure 3, it follows that the moisture effect is most actively revealed in sandy soils, weaker – in loamy soils, and it is very low in clayey soils.

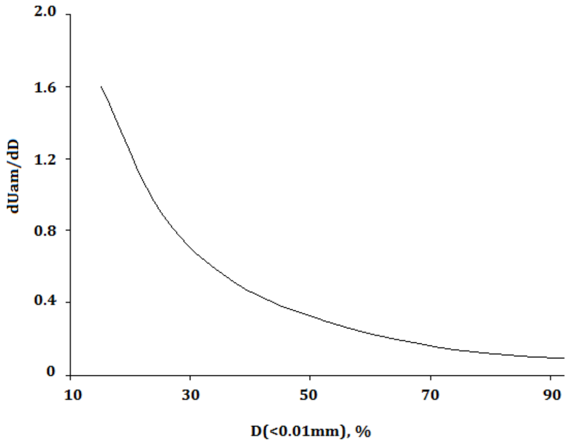

Figure 3. The change rate of moisture content (dUam/dD) depending on clay particle content in the soil.

At the same time, the bond energy of moisture with solid phase, on the contrary, is higher in more disperse soils. It is for that reason the dynamics of the thermal conductivity and thermal diffusivity factors decreases at transition from sandy to clayey particle-size composition. Thus, the structural-functional concept of thermophysical condition coordinates the quantitative interrelations between the basic soil-physical factors (*U, D* and *BD*) and the thermophysical indices (a_m, λ_K) of soils.

Conclusion

1. Soil-physical factors render many-valued effects on the character and the value of thermophysical indices of the soils of different genesis and particle-size composition. The most essential role in that belongs to the degree of soil moistening and the density of soil structure.

2. The developed structural-functional concept of thermophysical condition of soils enables revealing the quantitative interrelations between the soil moisture content, the dispersion degree, the density of structure and the factors of thermal transfer.

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