On the Correlation of Heat and Moisture Properties of Soils

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Introductory Remarks by Chairman

The great importance of thermal conductivity in soils not only for agriculture, but for many engineering problems, is becoming more and more realized. The bearing of the phase compositon (solid-liquid-gas) and of the dispersion and structural arrangement of these phases on thermal conductivity has been recognized and these factors have been taken into account to a greater or lesser extent in some of the available equations for approximate prediction of thermal conductivity in soils. A vexing phenomenon in all thermal conductivity measurements in moist soils is the water transfer that accompanies and modifies heat transfer. More knowledge on the character and the quantitative aspects of this coupling is seriously needed. Pure scientific analysis of similar phenomena in much simpler systems, such as the creeping of Helium II, has already proved to be rather a formidable job indicating that a semi-empirical, experimental approach must be applied in the case of soil systems in view of their well-known extreme complexity. The coupling of heat and moisture transfer must be related to the physical and physicochemical state of the water in the system under consideration. Flood in this symposium proposes to characterize this state by the use of absorption isotherms; others have utilized suction potentials for this purpose. Kolyasev for the same purpose of characterizing the water condition at certain moisture contents in specific soil systems employs the drying rate curves and the degree of water availability to plants. All these approaches are legitimate and valuable. The more of these approaches are developed, the greater are the chances that one may be found that is not only simple, but of wide applicability. This would enable the job to be done semi-empirically, but with sufficient accuracy for practical purposes, while the pure scientists continue to look for ultimate causes and mathematical correctness. In addition to presenting their combined theoretical and experimental approach, Kolyasev and his co-worker give an empirical formula and a nomographic chart on thermal conductivity of soils as a function of moisture content and dry density which differs somewhat from the well-known Kersten formulae.

●PROBLEMS of improving the thermal properties of soils are most actual and diverse.

The thermal conditions of soils may be influenced by different agrotechnical measures: hoeing, compaction, deep tillage, irrigation, etc. All these measures affect the soil heat conditions by changing its thermal characteristics: heat conductivity, thermal diffusivity and volume heat capacity. Consequently, in order to develop expedient agrotechnical measures for specific soil-climatic conditions, it is necessary, while cultivating various crops, to be acquainted with the correlation of the soil thermal characteristics and the soil properties.

As shown in previous investigations (2, 4), the thermal characteristics are widely dependent on the soil properties.

The thermal characteristics of the southern black earth (chernozem) have been determined. As regards its mechanical properties, the investigated soil may be considered as light loam. The specific weight of the solid phase shows the values of 2.5 – 2.7 gm/cm^3, while the bulk density if 1.2 – 1.5 gm/cm^3 at the depth of 0 – 100 cm.

The purpose of the present paper is to discuss the results of the investigation concerning the dependence of the soil thermal characteristics upon its density. The experiment has been conducted with the soils of destroyed structure, because for the solution of the problem it was necessary to vary the density at constant moisture content and to vary the moisture content at constant density, which is not feasible under field conditions.

Recently the Soviet specialists have developed a few methods enabling to determine the thermal characteristics of soils. The coefficient of thermal diffusivity "K", using the method of G.M. Kondratjev (3) based upon the principle of the regular regime, for a sample of cylindrical shape has been defined.

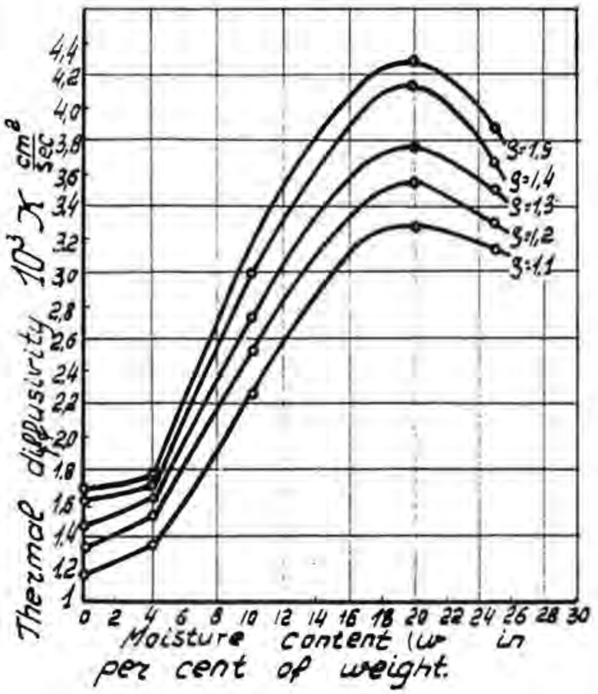

Figure 1.

In the course of the experiments the density ρ varied from 0.1 to 1.5 gm/cm^3 with increments of 0.1, while the moisture content w was characterized by the following terms: absolutely dry, air-dry, 10, 20 and 25 percent of moisture content based on dry weight.

The coefficient of thermal diffusivity has been measured for more than one hundred samples of plough layer soil. Identical measurements have been performed for the soil of the 80-100 cm layer. These "K" values differed from the plough layer "K" within the measurement accuracy. The conclusion suggests itself that for the southern black earth (chernozem) the coefficient of thermal diffusivity practically does not vary for the same density and moisture content. This may be explained by the uniformity of the soil dispersion in this layer. Therefore, in order to elucidate the principles of the "K" dependence upon moisture content and density the investigation was confined to the analysis of data for the plough layer.

The obtained values of $K = f(w)$ and $K = \zeta(\rho)$ are expressed graphically in Figures 1 and 2.

The volume heat capacity may be determined by means of the relation:

$$C\rho = (0.2 + \frac{w}{100})\ \rho, \text{ where}$$

$C\rho$ is the volume heat capacity;
w is the moisture content in percent of weight;
ρ is the density, and
0.2 is the specific heat capacity of heavy loams.

The volume heat capacity increases linearly with increasing moisture content and density.

The coefficient of heat conductivity λ has been estimated by means of the formula $\lambda = KC\rho$ and the obtained data are shown graphically in Figures 3 and 4.

The coefficient of heat conductivity for any moisture content and density may be determined by using the empirical formula, inferred by the authors:

$$\lambda = 10^{-3}\left[(2.1\ \rho^{\ 1.2-0.02w}\ e^{-0.007(w-20)^2}\ \rho^{0.8+0.02w})\ (0.02 + \frac{w}{100})\rho\right].$$

The formula being too complicated, a nomographic chart has been developed (Fig. 5), by means of which it is easy to determine all heat characteristics on the base of the predetermined values of moisture content and density; while knowing K, λ and ρ it is possible to determine the moisture content as well.

The coefficient of thermal diffusivity has been found also for soil samples with undisturbed structure. The "K" data obtained are somewhat smaller than in the case of the soils with destroyed structure, the value of the deviations not exceeding the experimental error.

Thus, the principles of the "K" relationship for the soils with destroyed structure may be used also for the soils under natural conditions.

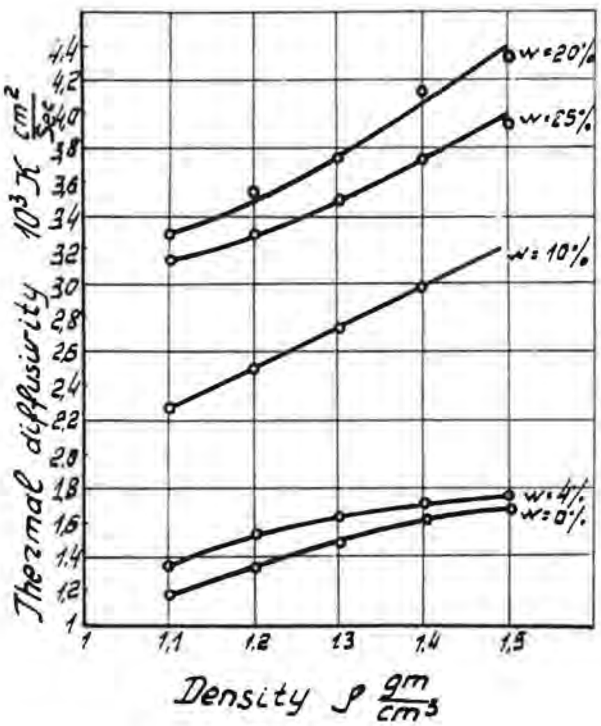

Figure 2.

On the Correlation of the Heat- and Water Properties of Soils

According to the data of previous investigations, K = f(w) increases to a maximum within the different limits of moisture content depending on the properties of the soil. For the fine-grained sand the "K" maximum is within 8 to 10 percent of moisture content, for the coarse-grained sand—within 5-8 percent, for the clay—within 24-28 percent. The character of the K = f(w) curves is different too: for the sandy soil the curve is convex, while for the clayey soil it is concave.

As every soil has its own water constants, the above experimental data permitted drawing a conclusion about the connection between the heat and water properties of the given soil.

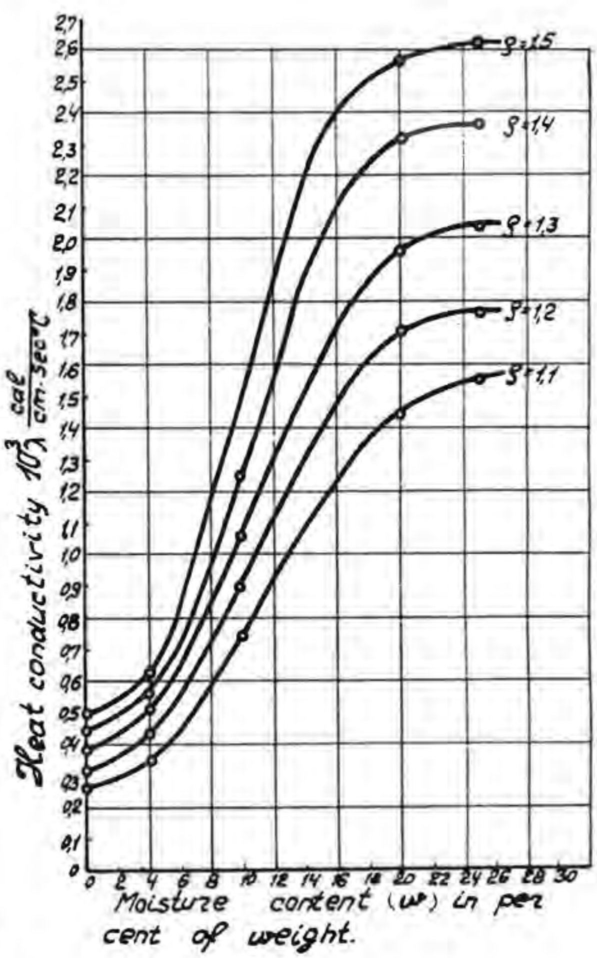

Figure 3.

The coefficients of heat conductivity and of thermal diffusivity for the given soil increase with increasing moisture content unequally within the different limits of moisture content. This fact confirms the nonuniform character of heat transfer at the different stages of wetting.

A hypothesis about the dependence of the heat transfer mechanism upon the forms of water in the soil has been proposed by A. F. Chudnovsky.

In dry soil, as in a dispersion system (solid body—gas) the heat flow passes not as a continuous front, but as separate flows in the direction of the smallest spacings be-

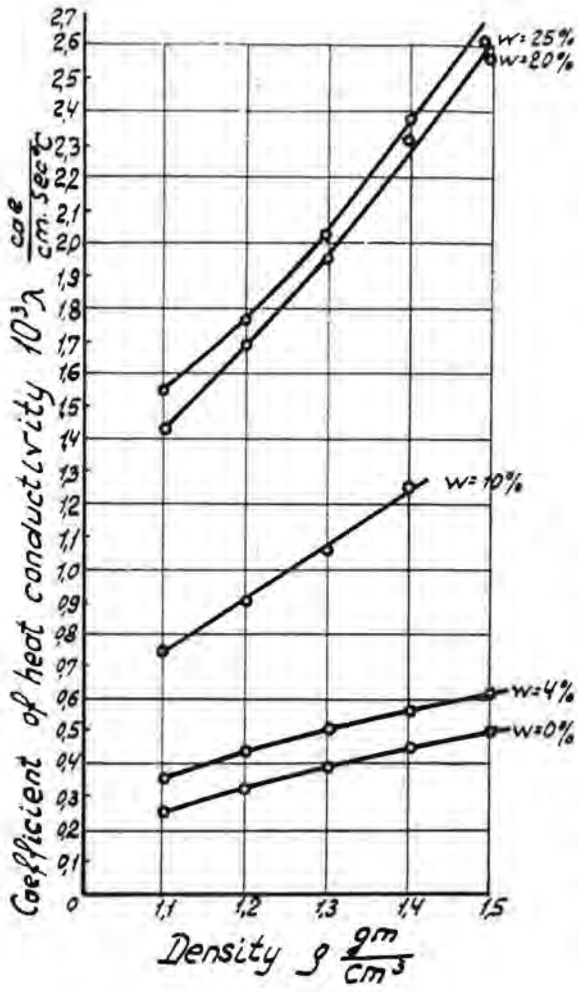

Figure 4.

tween the particles. The heat conductivity in the wet soil, as in a three-phase medium, is characterized by transferring heat through solid particles, water and air.

The value of heat conductivity depends on the shape, character and size of contacts of separate particles and on the quantity of water and air between them. Therefore, in order to ascertain the character of heat conductivity in wet soil, it is necessary to know the principles of the relationship between the soil particles and water for the different stages of wetting. Opinions concerning this problem differ, which again hampers the elucidation of the heat transfer process in soils.

In order to ascertain the connection between heat properties of the soil and its water properties, the so-called "theory of differential moisture" was used, which is the theory of the state and movement of water in soils developed by one of the authors on the base of laboratory and field tests. Following the theory of drying, F. E. Kolyasev developed a method for determining the mobility of water in soils in dependence of the soil moisture content. This method is founded on the rate of soil drying, because the rate of drying is connected with the rate of water movement; consequently it may characterize the degree of water mobility in soils at different moisture contents, as well as give an idea about the fundamental water properties of the soil, which determine the relation of the given soil to water ("Soil Science", ("Pochvovedenje"), No. 4, 1957).

The experimental data prove that the curve of drying versus moisture content $\frac{dw}{dt} = f(w)$ is not smooth, but shows a few bends (Fig. 6). This indicates different rates of water movement towards the evaporating surface.

On the base of the drying rate curves F. E. Kolyasev has developed a scheme for the water movement in soil which enables to determine:

1. The fundamental water constants (using the break points on the drying rate curve).
2. The prevalent mechanisms of soil water movement for different moisture contents.
3. The degree of soil water availability for the plants.

The classification of the whole scope of soil water is based upon the physical causes of water movement at different moisture contents of the soil, as well as on its interaction with the soil particles.

By means of the drying method the water constants of black earth (chernozem) were determined, these constants being complemented and confirmed by the field and laboratory tests conducted according to the usual methods.

Four break points have been obtained for the investigated soil on the drying rate curve which correspond to definite conceptions in agricultural practice. The first break corresponds to "field capacity", the second—to the "moisture content of plant growth retardation"; the third—to the "moisture content of steady plant wilting"; the fourth—to the "maximum hygroscopicity". According to the drying rate data a general

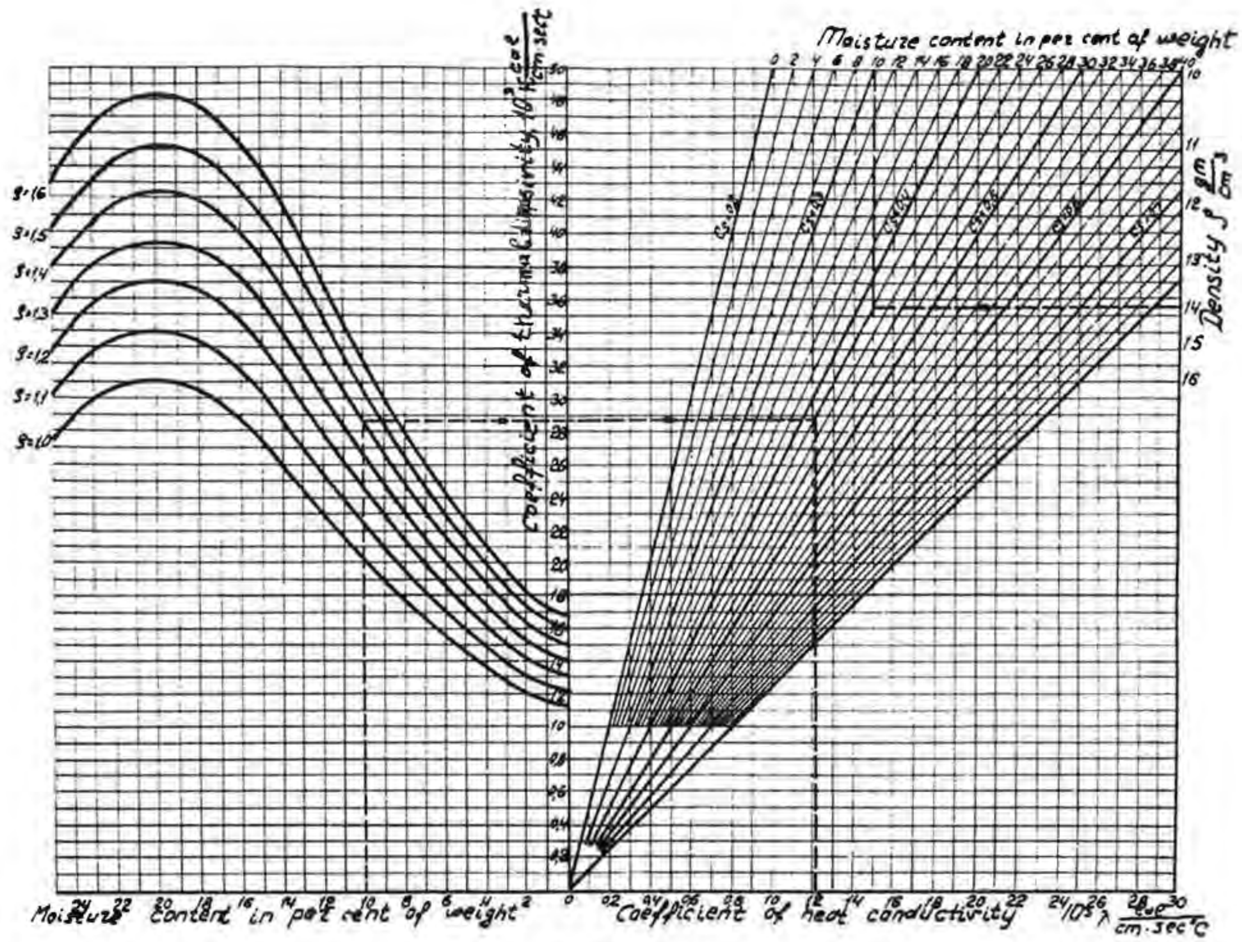

Figure 5.

scheme was developed by F. E. Kolyasev showing the predominance of different mechanisms in the soil water movement. An identical scheme for the southern black earth (chernozem) is given in Figure 7.

According to this scheme five mechanisms of water movement are ascertained: diffusion, film, film-meniscus, capillary and gravitational mechanisms. Such a conception of soil water movement provides the possibility to draw up a hypothesis about the heat transfer in humid soil as a function of the moisture content.

The relationship of $K = f(w)$ and $\lambda = \zeta(w)$ obtained in the course of the experiment may be explained if the values of "K" and " λ " are connected with the properties of soil water at the given stage of wetting and at a predetermined density.

The coefficients of thermal diffusivity and of heat conductivity increase with increasing density, the character of their increase being dependent on the moisture content.

If the soil is absolutely dry, the rate of increase in "K" and " λ " is greater at the lower density values, while at the higher values the increase slows down (Figs. 1 and 4).

The heat transfer in such kind of soil is accomplished mainly through the contacts between the soil particles, and with the increase of density evidently a certain limit of their drawing together and of the improvement of contact is reached.

The same condition for "K" and " λ " will be observed in the air-dry state, when their values are somewhat greater than in the absolutely dry state, because the sorbed water slightly improves the contacts.

At the 10 percent moisture content (film mechanism of water movement) "K" and " λ " increase rectilinearly with increasing density and their values increase sharply in magnitude as compared with the data for the air-dry condition. At this stage of wetting, water takes part in the heat transfer, creating at the points of the particles adjaceny certain water contacts—"bridges"—through which heat transfer is accomplished.

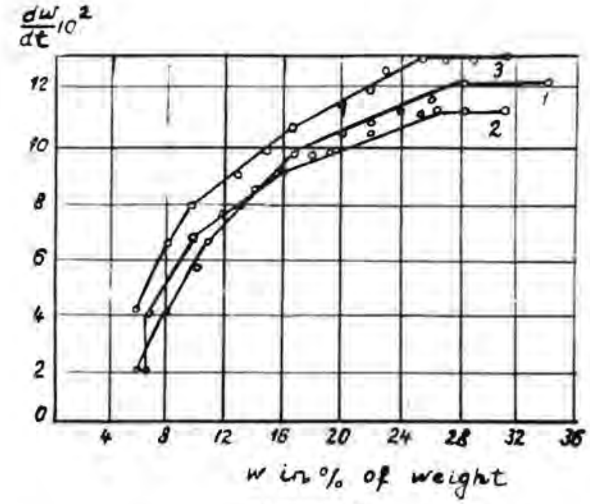

Figure 6.

The 20 percent moisture content is such a stage of wetting at which the film-meniscus mechanism of water movement changes into the capillary mechanism. At the given moisture content the values of "K" and "λ" continue to increase with increasing density and at high values of density their increase will be greater. The increase of density brings the particles closer together which results in shortening and widening of the "bridges", i.e., in the decrease of thermoresistance. Besides, the mass of the solid phase is increased, the heat conductivity of the latter being about 5 times greater than that of water. The heat transfer will proceed not over the separate "channel-bridges", but by means of a certain continuous flow of heat created through water and solid phase, the part of the latter in the heat transfer being predominant.

At the 25 percent moisture content the capillary mechanism of water movement prevails. The character of change of "K" and "λ" with increase in density is the same as at 20 percent, but the magnitude of "K" for all density values is lower than at 20 percent. It is to be supposed that as the moisture content increases in the interval where the

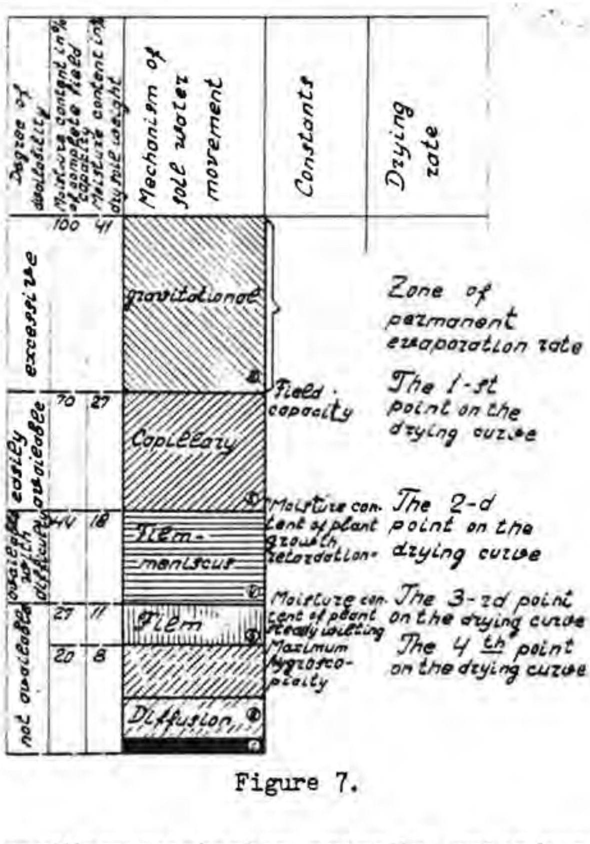

Figure 7.

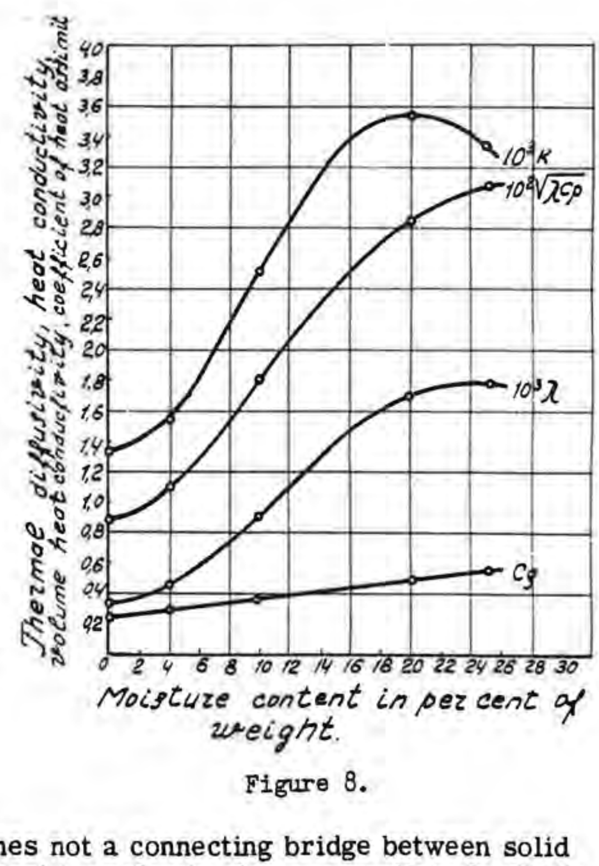

Figure 8.

capillary mechanism prevails, water becomes not a connecting bridge between solid particles, but a medium through which the heat transfer is also accomplished. While the quantity of water increases, its part in the heat transfer also increases and the rise of the heat conductivity coefficient slows down approaching the heat conductivity of water (Fig. 3). But as the volume heat capacity continues to increase with increasing moisture content, and as $K = \frac{\lambda}{C\rho}$, the coefficient of thermal diffusivity decreases with the further increase of moisture content (Fig. 8).

Hence the coefficient of thermal diffusivity increases with increasing moisture content and reaches its maximum at such a moisture content where the film-meniscus mechanism changes into the capillary mechanism. The latter condition corresponds to the moisture content determined by the constant—"moisture content of plant growth retardation."

Each type of soil is characterized by its water constants and this evidently explains the experimental fact, that the coefficient of thermal diffusivity for different soils reaches its maximum not at the same, but at different moisture contents.

Evidently the break point in the $K = f(w)$ curve will take place for all kinds of soils at the "moisture content of plant growth retardation."

There are reasons to suppose that the break points on the $K = f(w)$ curve will also exist at the moisture contents which correspond to the "maximum hydroscopicity" and to "steady plant wilting" constants.

This is a problem for further investigations which may be solved with the development of a method for continuous recording of the moisture content.

At present such a method is being developed at the Laboratory of Soil Physics at the Agrophysical Institute in Leningrad.

CONCLUSION

The basic principle underlying measures to improve the thermal properties of soils is the dependence of the soil thermal characteristics upon the moisture content and density. The thermal diffusivity which determines the warming up of the soil along its profile increases with increasing water content up to the "moisture content of plant growth retardation." Consequently, in the soil with a greater moisture content the rate of temperature equalization will be greater and the warming up throughout the profile will be more intensive. At the moisture content which is greater than the "moisture content of plant growth retardation" the warming up is slowed down, because "K" decreases with increasing moisture content.

Proceeding from the conjecture about the dependence of the heat transfer mechanism in wet soil upon the water transfer mechanism at different stages of wetting, it is possible to draw a conclusion about the existence ot a certain connection between the heat and water properties of a given soil.

The accumulation of experimental data on the dependence of thermal characteristics upon the moisture content for different soils accompanied by the determination of their water properties ensures the possibility of proving more extensively the theory of differential moisture content on the basis of which the heat transfer in moist soils has been explained.

REFERENCES

1. Kolyasev, F.E., "Water Movement in Soils and Some Ways for its Control." (a) "Problems of Agronomical Physics." Leningrad, 1957. (b) "Soil Science." ("Pochvovedenje") No. 4, 1957.

2. Kersten, M.S., "Thermal Properties of Soils." Engineering Experiment Station Bulletin. 1949, No. 28.

3. Kondratjev, G.M., "The Use of Regular Regime Method in Heat Conductivity Tests for Building Materials." Standardgiz, 1936.

4. Chudnovsky, A.F., "Heat Transfer in Dispersed Systems." State Publishing House (Gosizdat) for Technico-Theoretical Literature.

5. Gupalo, A.I., Bulletin of the Agrophysical Institute, No. 1, 1955.