

BEHAVIOR OF MOIST SOILS IN A THERMAL ENERGY FIELD¹

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ABSTRACT

An account is given of the soil thermal resistivity problem faced by the electric power industry and its co-operative engineering solution. Data obtained in this activity and collected from other sources are employed to check the validity of various concepts that have been developed to explain the phenomena observed when soils, composed of solid, liquid and gaseous phases, are placed in a thermal energy field. It is shown that formulas based on simple parallel or series arrangement of the component phases cannot account for the actual thermal transmission properties of moist soils. Nor can any one of the moisture transfer mechanisms, that have been proposed in explanation of the water movement associated with heat conduction in moist soils, by itself account for the observed magnitudes of thermal conductivity. Analysis of pertinent data renders it very probable that both evaporation-condensation and oriented film mechanisms must be involved in the coupled heat and moisture transport. What really takes place is an intricate interaction of a number of different events that can be understood qualitatively on the basis of the best available knowledge of soil-water interaction and its temperature dependence. Much work, however, remains to be done before a quantitative understanding can even be approached. The nature and magnitude of the remaining scientific problem can be appraised from the following pertinent statement by Szent-Györgyi (1958) "The complexity of the situation with its very subtle equilibria makes conditions most colorful and begins to resemble the subtle complexity which characterizes life."

INTRODUCTION

It is a pleasure and a privilege to participate in this symposium on the engineering aspects of the physico-chemical properties of soils, especially since it is being held in the Middle West which may justly be considered as the cradle of modern scientific and engineering endeavors in this field (Winterkorn, 1936b, 1937a, 1937b, 1940; Winterkorn and Eckert, 1940a, 1940b; Winterkorn and Moorman, 1941; Winterkorn, Gibbs and Fehrman, 1942; Winterkorn, 1946). The present paper deals with the behavior of moist soils and related multiphase polydispersed systems in a thermal energy field. Such systems usually possess at least one liquid and gaseous phase and one or more solid phases; their state of equilibrium depends on compo-

¹ Account of an engineering research project and of the physico-chemical significance of some of its results.

sition, temperature and pressure. The response of such systems upon being placed in a thermal energy field is functionally connected with the respective absolute volumes and material properties of the various phases, their degree and geometry of dispersion and the interaction between the various phases and their components. Obviously, such systems are of great complexity and so is their response to an applied thermal energy field.

Despite their forbidding complexity, systems of this type have been utilized and studied since the dawn of history because of their outstanding importance for the human race. Specific solutions of pertinent problems related to agricultural and other activities have been developed in every age with greater or lesser success. An impressive example is provided by the "aerial wells" which the ancient Greeks built on the Crimean Peninsula as a source of their water supply, utilizing the effect of natural temperature fluctuations on the condensation and adsorption of water vapor on mineral surfaces (Aristotle, 322 B.C.; Volger 1877; Chaptal, 1932; Winterkorn, 1944, 1955d). This and similar historical achievements were based on slowly accumulated empirical knowledge which every once in a while was co-ordinated within the framework of the dominant philosophy of the day and put to unexpected use by the art of genius.

It is one of the primary aims of science to reduce the areas in which only the specially gifted can achieve success and to place them more and more into the realm of scientific organization and reproducibility. Unfortunately, the very complexity of moist soil systems renders them unattractive to the pure scientist and makes significant experimental study quite expensive. As a result, these systems and their response to thermal energy fields have been studied only sporadically and usually with specific engineering objectives in mind. Among the latter were: explanation and control of water accumulation underneath pavements in the absence of precipitation or capillary movement from a ground-water supply, and water transport in frost heaving and deterioration of stabilized soil systems (Winterkorn, 1944, 1946, 1955c). A certain amount of clarification, however, had been achieved with respect to the condition of water in moist soil systems, the effect of temperature on this condition and movement of water in soils under various energy potentials (Winterkorn and Baver, 1934; Baver and Winterkorn, 1935; Winterkorn, 1936a, 1947; Winterkorn and Choudhury, 1949; Winterkorn, 1955a, 1958a, 1958b).

SOIL THERMAL PROBLEMS FACED BY THE ELECTRIC POWER INDUSTRY

A chance to take a new look at the behavior of moist soil systems under the influence of a thermal energy field was provided by the concern of the electric power industry over the rapid increase in recent years of failures of buried power cables due, at least in part, to the inability of the sur-

rounding soil to dissipate the Joule and dielectric heat developed by the alternating electric current. Aggravation of this problem in recent years derives from the fact that large-scale use of refrigerating and air conditioning equipment has shifted the peak of the power load to the summer season when soils are normally at their lowest moisture content and hence their lowest thermal conductivity or highest thermal resistivity (ρ). The engineering situation existing in 1956 was well described by Burrell (1956).

With respect to soil thermal resistivity, there was available a considerable body of experimental data of varying dependability and several equations for calculating this property from other soil parameters. These equations ranged from the empirical relationships developed by Kersten (1949) on the basis of experimental work on a wide range of soil materials, to others based on the theoretical and model concepts of Maxwell (1873), Burger (1919) and Eucken and Kuhn (1928). Some had been reduced to nomograph form for easier practical use. Each method had specific advantages and disadvantages and none held equally well for the whole range of soil moisture content, density, granulometry and mineral composition encountered in practice (De Vries, 1952). In addition, the relative scarcity of experimental data for which all pertinent factors were given made it difficult if not impossible to decide whether the respective theory or the experiment gave more reliable data.

The power and utilities industries were doing the best they could under the existing circumstances. Conduit systems were designed mainly on the basis of experience which is always a good, if not the most economical, guide. Progressive companies were making thermal resistivity surveys of existing and projected cable routes, but did not make simultaneous moisture and density determinations from which variation of thermal resistivity with seasonal variations in moisture conditions could be predicted. For these resistivity surveys, the industry had developed a suitable instrument in the form of the thermal needle. While the industry had also made determinations of the seasonal variations of soil thermal resistivity, the respective data had not been correlated with soil density and moisture content, absence or presence and relative location of permanent or temporary water tables, or with other soil and climatic factors that could furnish explanations for the observed data and permit their use for the purpose of extrapolation and theoretical development. The same held true for temperature surveys made on conduit surfaces and in surrounding soils.

The electric power industry recognized the insufficiency of what was known and being done, and gave a clear formulation of the main problems facing it in the form of the following seven questions: (1) What are the fundamental factors that determine the effective thermal resistivity of various soil types? (2) What are the reasons for observed seasonal variations of effective thermal resistivity in some soils and not in others? (3) What are

the factors that influence moisture migration, and what critical conditions "trigger" soil thermal instability? (4) What range of effective thermal resistivity values apply in various parts of the country or, more objectively, what values should be used for specific soil types? How should these values be adjusted for different depths of burial and for changes in climatic conditions? (5) What limitations must be observed in the operations of underground cable lines to insure stable soil thermal conditions? (6) What artificial means are practical for controlling the thermal behavior characteristics of various soil types? (7) What means can be established to relate findings of soil thermal resistivity properties to proposed or existing cable routes with a minimum of soil sampling, mechanical analysis or testing of an extended nature (Burrell, 1956)?

These questions are obviously of an engineering nature and the answers expected by the industry were to be of the same nature, *i.e.* they were to be directly applicable to engineering design and control. Significant and valuable engineering answers must be based on the best available scientific and theoretical knowledge; but, since such knowledge is never complete, that which is available must be rounded up with engineering judgment in order to become a useful tool of the engineering art. This shaping of engineering tools out of available scientific and practical knowledge often involves not only a realistic assessment of what knowledge is actually available and significant, but also, as it was in the present case, a supplementation by new experimental data and more adequate theoretical concepts, and by the development of improved test procedures.

ENGINEERING SOLUTION OF THE SOIL THERMAL PROBLEMS FACED BY THE ELECTRIC POWER INDUSTRY

The engineering solution developed for the soil thermal problems of the electric power industry is a matter of record and has already been reduced to practice. Pertinent scientific publications on this project from the Soil Physics Laboratory of Princeton University are by Roy and Winterkorn (1957), van Rooyen and Winterkorn (1957, 1959) and Winterkorn (1958b, 1958c).

The reduction to practice of the results of the university research combined with the data and experience developed by the electric power industry is recorded in the papers by Wiseman and Burrell (1960), Del Mar, Burrell and Bauer (1960), Fink (1960), Sinclair, Buller and Benham (1960), Brookes and McGrath (1960) and Cameron and Brookes (1960).

It is impossible within the time and space allowed to present here even the main features of the engineering solution. Also, there is no substitute for perusing the cited reports and publications if one wants to gain useful

knowledge. It will, however, be justified and within the scope of this symposium to present a limited number of experimental findings and to point out their physico-chemical significance.

THE PHYSICO-CHEMICAL SIGNIFICANCE OF CERTAIN TEST RESULTS

I. General Orientation

In the following, the resistivity of a soil to the passage of thermal energy will be given in thermal ohms, *i.e.* °C cm/W. For general orientation, average resistivity values are presented in Table 1 for some of the more

TABLE 1.—AVERAGE RESISTIVITY VALUES IN THERMAL OHMS (RHO) FOR SOME SOIL CONSTITUENTS AND ALLIED MATERIALS

Material	Rho
Quartz	7.9
Quartz ⊥	14.9
Quartz, random orientation	11.0
Quartz glass	79.0
Granite	26-58
CaCO ₃ ⊥	26.3
Marble	34-48
Limestone, dense	45
Ice	45
Sandstone	50
Dolomite	58
Slate	67
Water	165
Mica ⊥	170
Pine wood	265
Pine wood ⊥	608
Organic material wet	400
Organic material dry	700
Air	4000

important soil constituents and related substances under normal conditions. According to these data, quartz is by far the best heat conductor among the normal soil components. Also it is significant that the thermal resistivity of quartz glass is ten times that of quartz ||, a fact which demonstrates the importance of atomic order. No data are, of course, available on single crystals of the clay minerals though it is to be expected that the

blocky kaolinitic clays have a lower average resistivity than the montmorillonite clays. One may obtain a minimum average value for clays by assuming that it will be of the same order of magnitude as that for mica and that the ratio for the mica \perp to the mica \parallel value is similar to that for pine wood \perp to pine wood \parallel . This way the mica \parallel value becomes about 74 and the average mica resistivity 122. The mica \parallel value is practically identical with that normally given for slate, a fact which tends to justify the employed reasoning. Accordingly, an average thermal resistivity of about 122 is the minimum that one can reasonably expect for clay minerals.

II. Dry Particulate Systems

Table 2 gives average resistivity data for solid quartz and for systems composed of air and crushed quartz particles of different sizes and different degrees of densification. It is the latter rather than the average particle size that plays the determinant role with respect to thermal resistivity.

TABLE 2.—THERMAL RESISTIVITY VALUES FOR SOLID QUARTZ AND FOR CRUSHED QUARTZ PARTICLES OF DIFFERENT SIZES COMPACTED TO VARYING POROSITIES

Material	Density (g/cm ³)	Percent Air by Volume	Thermal Resistivity (°C cm/W)
Solid quartz	2.64	0	11
Crushed	1.307	50.6	573
	1.512	42.7	392
Finely crushed	0.824	68.9	1270
	1.600	39.4	228

In Fig. 1 are plotted thermal resistivity *vs.* porosity data of dry soil systems represented by two types of crushed quartz sand, two thermal sands which are sands so graded as to give a high density of compaction and containing a small amount of kaolinite clay, one Russian chernozem soil reported by Kolyasev and Gupalo (1958) and American silt-clay soils reported by Smith and Byers (1938). This graph shows the following interesting facts:

(1) At porosities above 50 percent for the quartz sands and the Russian chernozem soil and above 66 percent for the American silt-clay soils, the resistivity *vs.* porosity curves have approximately the same slope as a theoretical curve for the product of the resistivity of air and the air-filled porosity. The measured resistivity values for the quartz and chernozem systems, however, are approximately 1400 units smaller than those on the theoretical curve for the same porosities.

(2) At porosities of about 50 percent, the soils and sands possess approximately the same resistivity values. Use of a simple mixture formula for a resistivity value of 600 rho at a porosity of 50 percent results in a negative rho value of -2800 for the solid phase. By use of the same formula

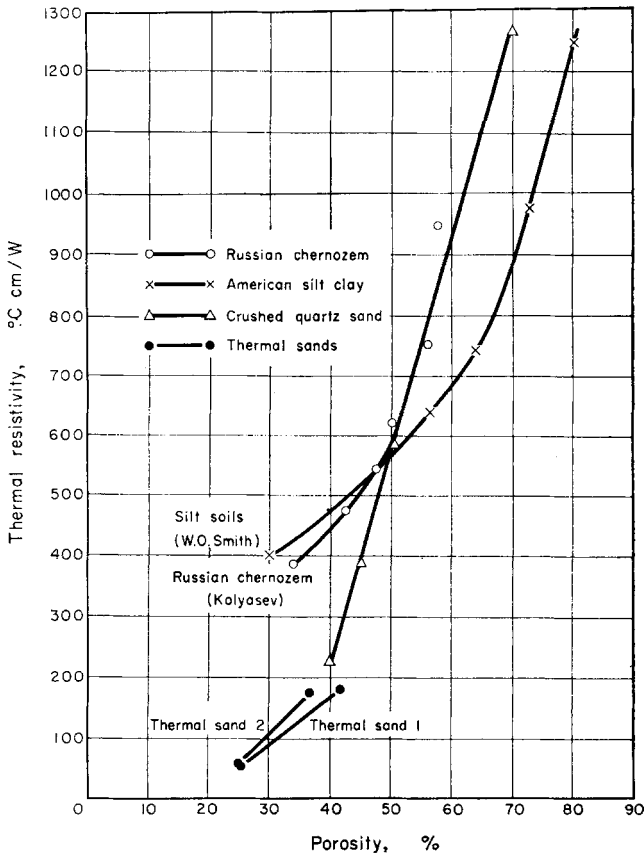


FIGURE 1.—Relationship between thermal resistivity and porosity of dry soils and sands.

employing the conductivities, *i.e.* the reciprocals of the resistivities, at a porosity of 50 percent one arrives at a value of about 321 rho.

(3) Below a porosity of 50 percent, the resistivities of the chernozem and silt-clay soils fall on curves whose extrapolated intercepts with the ordinate will probably give a fair value of the average resistivities of their solid constituents at zero porosity, while the rapid decrease in thermal resistivity of the crushed quartz sands continues to a porosity of less than 40 percent.

(4) The curves for the thermal sands represent a logical continuation of the crushed quartz curve down to a porosity between 20 and 25 percent whence they too may be expected to follow a curve that intercepts the ordinate at the average resistivity value for solid quartz. The physical significance of the mixture formulas employed and the underlying concepts,

TABLE 3.—APPROXIMATE PERCENTAGES OF VOLUMES OF COMMON SOIL MINERALS OCCUPIED BY THE COMPONENT IONS

Soil Minerals	Ions	Volume (percent)
Orthoclase	K ⁺	11.12
	Al ³⁺	0.91
	3 Si ⁴⁺	0.86
	8 O ²⁻	87.20
Albite	Na ⁺	4.77
	Al ³⁺	0.97
	3 Si ⁴⁺	0.92
	8 O ²⁻	93.20
Muscovite	K ⁺	7.65
	3 Al ³⁺	1.87
	3 Si ⁴⁺	0.59
	12 O ²⁻	89.90
	2 H ²⁺	0.0
Quartz	Si ⁴⁺	1.29
	2 O ²⁻	98.71
Corundum	2 Al ³⁺	5.2
	3 O ²⁻	94.8

Ionic volumes in Å³: Si⁴⁺, 0.252; Al³⁺, 0.796; Na⁺, 3.94; K⁺, 9.85; O²⁻, 9.65; F⁻, 9.85.

as well as their advantages and limitations, have been discussed in detail by van Rooyen and Winterkorn (1957, 1959).

The rapid decrease in thermal resistivity with decreasing porosity, especially at the higher porosity values which, if extrapolated to zero porosity, would give negative resistivities for the solid phases, indicates that for these materials the efficiency of thermal transmission through a contact interface may be of the same order as that within the individual grains. This is not surprising if one keeps in mind that the dry soil constituents contain adsorbed oxygen films which form a conductive bedding between two contacting particles and that the intrinsic transmission properties of this bedding do not differ much from those of typical soil minerals which from a volumetric point of view consist mainly of oxygen. The latter is illustrated by the data in Table 3.

According to Debye (Kitell, 1956), the thermal conductivity of pure crystalline solids can be calculated from the equation:

$$k = \frac{1}{3} c u \lambda,$$

where k = thermal conductivity (cal/cm °C sec),

c = heat capacity of the lattice waves or phonons (cal/cm³ °C),

u = velocity of sound (cm/sec), and

λ = mean free path of phonon.

Taking the respective values for quartz || as $c = 0.48$; $k = 0.03$; and $u = 5 \times 10^5$, we arrive at a $\lambda_1 = 4 \times 10^{-7}$ cm for quartz || and of $\lambda_2 = 4 \times 10^{-8}$ cm for quartz glass. The value of λ_2 is of the order of an oxygen film a few molecules thick while that for λ_1 corresponds to a film thickness of ten times as many oxygen molecules. Hence, it is quite possible that the thermal resistivity of well ordered, condensed oxygen films on the surfaces of soil minerals may fall within a range of values as low as that from 11 to 70. The latter value practically coincides with that of 74 previously estimated as quite probable for mica || and possibly for a minimum theoretical value of the thermal resistivity of clay minerals.

III. Behavior of Moist Soil Systems

Of greater theoretical and practical interest than the behavior of dry soil materials is that of moist soil systems. Fig. 2 shows data obtained by Kolyasev and Gupalo (1958) on a chernozem soil from southern Russia at different densities and moisture contents. The original data were transformed into thermal ohms and were plotted against the fraction of the total porosity that was filled with water at the respective moisture contents and densities given by the authors. The graph shows the significant fact that the actual volume filled by the solid soil particles in the system has a considerable influence on the thermal resistivity in both the very dry and wet states; however, when about 20 to 33 percent of the pore space existing at the different densities is filled with water, then the volume occupied by the solid soil particles in the system plays only a secondary role with respect to the thermal resistivity.

According to Kolyasev and Gupalo (1958), different thermal transfer mechanisms come into play with increasing moisture content. These are:

(1) In the absolutely dry state, increase in density increases the number of contacts between particles and hence the thermal conductivity.

(2) Increasing moisture content up to about 10 percent by weight in the case of the chernozem soil is adsorbed around the points of contact, improving the contact between particles and aiding heat transfer.

(3) From about 10 percent moisture on, the water films around the soil particles form a continuous sheet over the internal soil surface and

take part in the heat transmission by water movement in the film phase.

(4) At about 20 percent of moisture, the film mechanism of water movement changes into the capillary mechanism. Heat transfer proceeds no longer almost exclusively over the separate "channel-bridges," but by means of a certain continuous flow system through water and solid phase

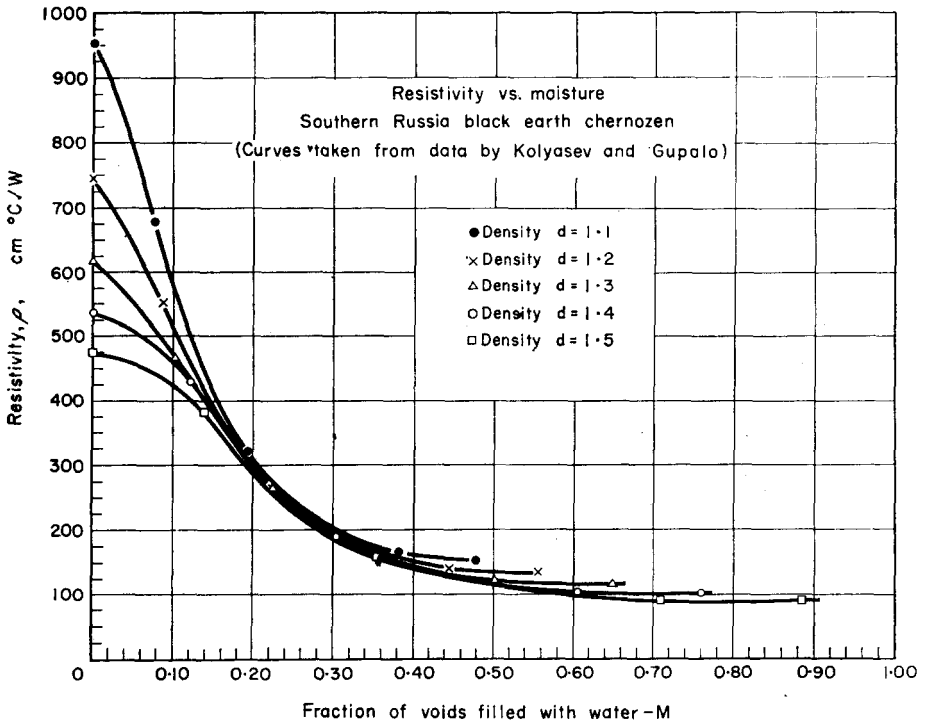


FIGURE 2.—Resistivity vs. moisture content for Black Earth from Southern Russia for various dry densities.

with the heat transmission on the solid phase still dominating the picture.

(5) From 25 percent on, the capillary mechanism prevails. As the quantity of water increases, its part in heat transmission also increases and the rate of increase of the thermal transmission coefficient slows down approaching the contribution from the thermal conductivity of water that replaces the air in the pores and reduces the area of existing air-water interfaces.

The observations of Kolyasev and Gupalo (1958) are essentially correct. They correspond with our own experience and the picture developed therefrom on soil-water interactions and water conduction in soils (Winterkorn,

1958a), but the physical picture becomes clearer if the absolute volumes occupied by the solid, liquid and gaseous phases of a soil system are considered instead of giving moisture content as a percentage of the weight of the solid phase (Winterkorn and Choudhury, 1949). This is evident from Fig. 2, as compared with the original graphs of Kolyasev and Gupalo (1958), in which thermal conductivities are plotted against moisture content

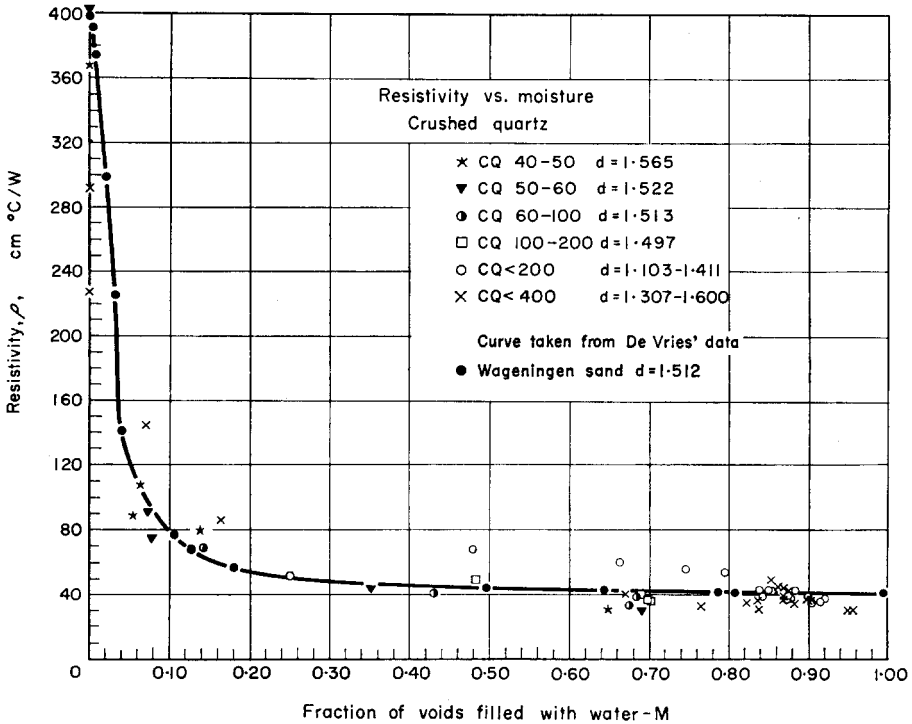


FIGURE 3.—Resistivity versus moisture content for several size ranges of crushed quartz sand at various dry densities.

in weight percentages, and also from Figs. 3 to 7. Obviously, at constant absolute volume of solids there is little if any change in thermal conductivity or resistivity with increase in moisture content after a certain percentage of the soil pore space has been filled with water. This indicates that a more effective thermal transmission mechanism, associated with air-water interfaces and with the presence of continuous or dispersed vapor phases, is gradually being replaced by a less effective one. The range in which this replacement occurs coincides with that in which considerable moisture movement takes place upon application of a thermal gradient.

IV. *The Problem of Moisture Movement Under a Thermal Gradient*

The available evidence makes it clear that the thermal resistivity of soils at natural moisture contents is very closely related to the problem of moisture movement under thermal gradients. This problem is quite complex and a goodly part of a recent international symposium of the Highway Research Board (1958) has been devoted to its elucidation. While a number of mechanisms have been proposed with particular emphasis on transportation either in the vapor or in the film phase or even in a solid-solution phase, it has become more and more evident that such mechanisms cannot be exclusive but that nature employs every mechanism that scientists can develop on the basis of the experimental evidence, though to different extents in the case of different soils and soil conditions (Smith, 1939; Fink, 1960; Winterkorn, 1955 a, 1955 b).

In 1947, Winterkorn proposed that differentiation might be made between predominant vapor phase or film water transport on the basis of thermal conductivity, since the former should yield a larger thermal transfer because of the latent heat of vaporization. Table 4 contains experimental

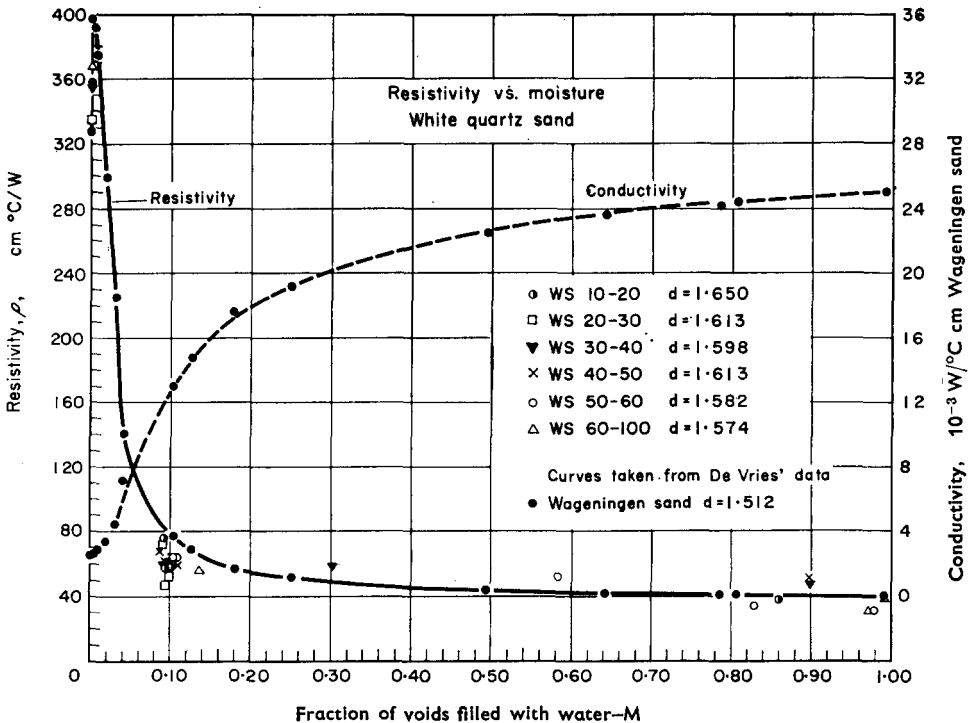


FIGURE 4.—Resistivity versus moisture content for several size ranges of natural white sands at similar densities.

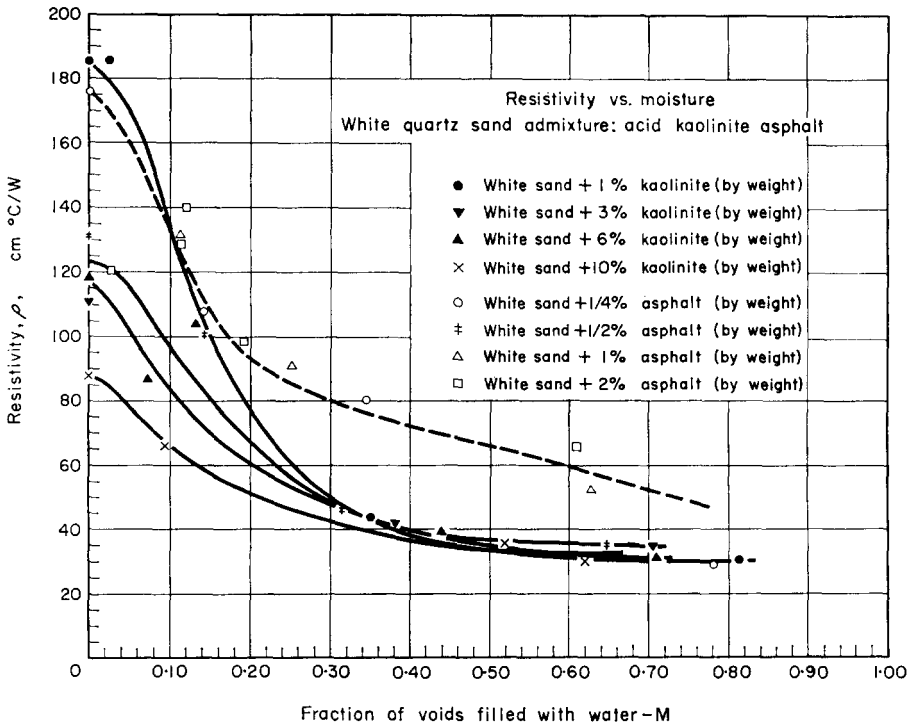


FIGURE 5.—Resistivity versus moisture content for thermal sand 1 at different dry densities.

TABLE 4.—THERMO-OSMOTIC MOISTURE TRANSMISSION COEFFICIENTS FOR H-KAOLINITE, H-MONTMORILLONITE AND H-GRUNDITE CLAYS AND FOR NATURAL AND SEVERAL HOMOIONIC MODIFICATIONS OF NEW JERSEY HAGERSTOWN SOIL IN THE MOISTURE RANGE OF THE PLASTIC LIMIT

Soil Material	Percent H ₂ O per Dry Weight of Soil	Thermo-osmotic Transmission Coefficient (cm ³ /cm ² sec per °C/cm × 10 ⁶)
H-kaolinite	30.6	3.4
H-illite (grundite)	23.5	1.6
H-montmorillonite	61.8	1.9
Natural	23.1	3.7
K	21.9	2.5
Mg	22.7	2.2
H	22.5	1.9
Cu	22.7	1.6
Al	23.1	1.5
Na	21.5	0.9

data on "thermo-osmotic" transmission coefficients for several different clay- and soil-water systems at moisture contents corresponding to the respective plastic limits in the vicinity of which thermal moisture transfer is a maximum (Gowda and Winterkorn, 1949). Selecting a transmission coefficient of $3 \times 10^{-6} \text{ cm}^3/\text{cm}^2 \text{ sec per } ^\circ\text{C}/\text{cm}$ and a latent heat of evaporation of 580 cal/g at 30 °C, we can calculate a contribution to thermal transmission from an assumed evaporation condensation mechanism of:

$$3 \times 10^{-6} \times 580 = 1.7 \times 10^{-3} \text{ cal}/\text{cm}^2 \text{ sec per } ^\circ\text{C}/\text{cm}.$$

This corresponds to a contribution of $7.3 \times 10^{-3} \text{ W}/\text{cm}^2 \text{ sec per } ^\circ\text{C}/\text{cm}$.

A contribution to the thermal conductivity, of this order of magnitude, also could be accounted for by assuming that the part of the water film proximal to the solid particle surfaces as well as the oriented water layer at the internal air-water interface are in such condition or state that they possess thermal resistivity properties between those of free water and normal ice. According to Henniker and McBain (1948), the oriented water at the air-water interface is several hundred molecules thick—of the same

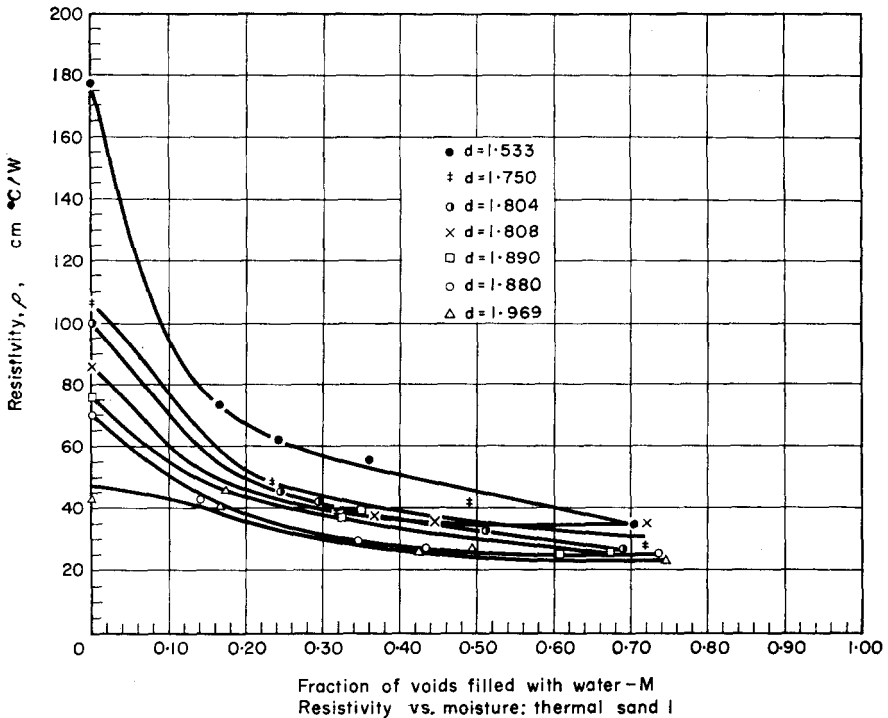


FIGURE 6.—Resistivity versus moisture content for thermal sand 2 at different dry densities.

order of magnitude as the thickness of the water films at the plastic limit.

In the face of the seeming equality in efficiency of heat transport by means of either an evaporation–condensation or oriented film conduction mechanism in soil systems containing solid, liquid and gaseous phases, the question remains whether either one by itself could account for the level of actually observed resistivity values. Sinclair, Buller and Benham (1960) analyzed all soil thermal resistivity data they could obtain and reported the following findings:

Sand.—Of 919 rho-values for sands of different densities and ranging in water content from zero to saturation, the average was 70.9 and the median 56 °C – cm/W. Fifty percent of the readings fell within the 33 and 77 bands.

Clay.—Of 801 rho values determined on moist clays, the average was 54.9 and the median 54 °C – cm/W. Fifty percent of the readings fell within the 49 and 62 bands.

Sandy clay.—Of 329 rho values determined on sandy clays of various moisture contents, the average was 53.1 and the median 50 °C – cm/W.

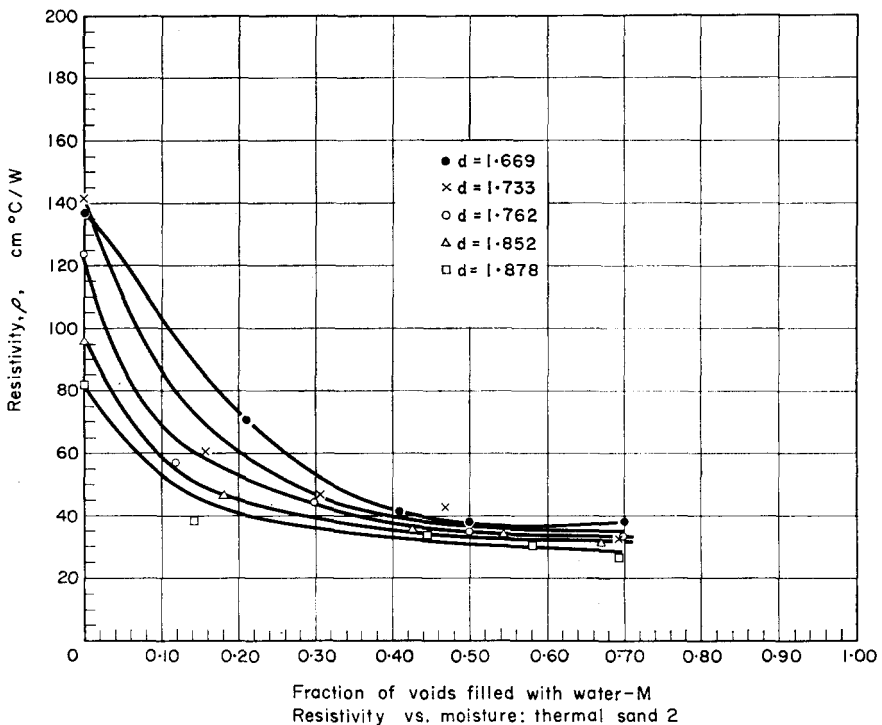


FIGURE 7.—Resistivity versus moisture content for white quartz sand with small amounts of admixtures.

Assuming the following reasonable values for a moist clay soil:

thermal resistivity = 55 °C – cm/W.

Volume percent of: solids = 50,
 water = 40,
 air = 10,

rho for the pure clay substance = 300 °C – cm/W,

rho for air = 4000 °C – cm/W,

and with straight additivity of the contributions to thermal conduction by the different phases, we obtain for the system:

$$k(\text{system}) = \frac{1}{\rho(\text{system})} = \frac{0.5}{300} + \frac{0.4}{165} + \frac{0.1}{4000}$$

$k(\text{system}) = 0.0041 \text{ W}/^\circ\text{C} - \text{cm}$ or $\rho(\text{system}) = 243 \text{ }^\circ\text{C} - \text{cm}/\text{W}$. If we add to this summation of phase conductivities the previously calculated average value of $7.3 \times 10^{-3} \text{ W}/^\circ\text{C} - \text{cm}$ as a contribution from an evaporation condensation mechanism, we obtain:

$k(\text{system}) = 0.0114 \text{ W}/^\circ\text{C} - \text{cm}$ or $\rho(\text{system}) = 87.6 \text{ }^\circ\text{C} - \text{cm}/\text{W}$; addition of an equal amount for incremental contribution from an oriented film transfer mechanism gives, finally:

$$k(\text{system}) = 0.0187 \text{ W}/^\circ\text{C} - \text{cm} \text{ or } \rho(\text{system}) = 53.5 \text{ }^\circ\text{C} - \text{cm}/\text{W}.$$

The last value compares well with the median value of 54 °C – cm/W found by Sinclair, Buller and Benham (1960) for moist clays.

In the light of the experimental evidence available and its theoretical evaluation, there seems to be little room for doubt that not just one but several and possibly all mechanisms of heat and moisture conduction in soils that so far have been developed on a rational scientific basis contribute to the total observed phenomenon. The considerable difference in thermal conductivity reported by Woodside and Cliffe (1959) for identical moist soil systems located, respectively, above and below a heated plate attests to the presence of an evaporation–condensation mechanism whose effectiveness is influenced by the lesser weight of the H₂O molecule as compared with those of the N₂, O₂ and CO₂ molecules which are the normal constituents of soil-air. The almost instantaneous establishment of a measurable electric field within a moist clay specimen upon application of a hot plate on one end and a cold plate on the other, long before establishment of a thermal gradient within the sample, points to the existence of a structure of oriented water molecules that possesses sufficient rigidity to transmit the electric disturbance caused by the temperature shock and to hold the impressed electric field (Winterkorn, 1955b) The described phenomenon is closely analogous to the hot–cold perception of the human skin and its transmission through the central nervous system. As a matter of fact, further disentanglement of the complexities of the behavior of moist soil systems in a thermal

energy field is probably of greater importance for a possible future understanding of the phenomena occurring in living systems than for soil engineering (Szent-Györgyi, 1958; Winterkorn, 1958b).

SUMMARY

An engineering problem concerning the behavior of moist soils in a thermal energy field has been described, and the solution accomplished co-operatively by the Insulated Conductor Committee of the American Institute of Electrical Engineers and the Soil Physics Laboratory of Princeton University has been traced and documented.

Certain physical and physico-chemical data, developed or collected and co-ordinated during this project, have been reanalyzed for the purpose of a better understanding of the various mechanisms that may play a part in the heat and moisture conduction observed when moist soils are placed in a thermal energy field, and of assaying the relative contributions of particular mechanisms to the total reaction picture.

The experimental evidence presented and its theoretical evaluation render it very probable that the several proposed mechanisms are not exclusive but must work together in order to account for the low values of thermal resistivity actually determined for moist clay soils. The conclusions drawn are in close harmony with the presently available understanding of the interaction of soil minerals with the water substance and the known temperature dependence of such interaction.

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