fairly constant. This indicates that the pore sizes for the different classifications in this case must be of approximately the same order.

In Figure 4 the points belonging to samples from test holes A_0, A_9, B_1, and B_6 are marked X. These test holes are located outside the pavement subject to entirely different conditions with regard to water absorption. This explains why the points marked X fall outside the straight lines established by the samples taken from underneath the pavement.

Conclusion

In this case the moisture analyses show that the water content of the ground beneath the concrete pavement is considerably less than what corresponds to full capillary saturation and, of course, even more so if compared to water content by complete submergence.

In districts with weather conditions like those in this country the results indicate the justification of determining the bearing capacity of the ground for a moisture content corresponding to a certain percentage of that with full capillary saturation.

However, the investigation is far too limited to permit drawing of specific conclusions particularly with regard to what percentage of the capillary saturation could be used in estimating the bearing value of different classes of soil.

DISTRIBUTION OF CAPILLARY MOISTURE AT EQUILIBRIUM IN STRATIFIED SOIL

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The rise and retention of capillary moisture in the soil above a free-water table are phenomena of considerable importance in highway engineering, since they influence, to a very great extent, the moisture content and therefore the bearing capacity of highway pavement subgrades. The movement of capillary water upward from a free-water table is also of prime importance during the growth of ice lenses, which result in frost heave and subsequent frost boil conditions.

It has been pointed out previously (2, 3) that the free-energy concept of soil moisture provides a valuable tool for the study of capillary water movements in soil subgrades and that the terminal accumulated moisture content in a subgrade beneath an impervious pavement is a function of the capillary potential of the soil. All of the sorption curves (capillary potential versus moisture content) presented in conjunction with the previous discussions were for completely homogeneous soils. Since highway subgrades are frequently non-homogeneous, it is of interest to study the character of the sorption curves of stratified soils. This paper presents a discussion of the theoretical aspects of free energy applied to stratified soil and a comparison of the equilibrium moisture content at various elevations above a free water surface in two experimental stratified soil columns with the theoretical moisture distribution.

The free energy of a system may be defined as the work performed to change it from one state to another. This work may, in general, be separated into two parts; the work of expansion due to changes in temperature and pressure and mechanical work. According to Edlefsen and Anderson, an incremental change in free energy may be represented by the equation (1, p. 85):

$$df = -sdT + vdP - dw_m \qquad (1)$$

in which

- df = change in free energy
- s = entropy of the system
- dT = change in temperature
- v = specific volume
- dP = change in pressure
- dw_m = change in mechanical work

Under isothermal and isobaric conditions, dT and dP are equal to zero and equation (1) becomes

$$df = -dw_m \tag{2}$$

In the field of soil moisture, the datum for measuring the change in energy is usually taken as free, pure water. Therefore the difference between the absolute free energy of free, pure water and that of the moisture at any point in a soil represents the specific free energy, or simply the free energy of the soil moisture. In other words, the free energy, Δf, of soil moisture is the energy (aside from the work of expansion against atmospheric pressure) required to change it from free, pure water to the state in which it exists in the soil.

When the temperature and pressure on the soil water remain constant, the free energy is analogous to a mechanical or hydraulic potential. This potential is called capillary potential or pressure potential. It is this limited concept of free energy which is usually employed in studies of unsaturated soil moisture movements in the liquid phase, although there is little doubt that the more general concept will need to be employed before complete understanding of problems in this field can be achieved. This would seem to be particularly true in problems of unsaturated moisture flow associated with frost heave and frost boils.

The free energy of unsaturated soil moisture is equal to the sum of several components of free energies. Thus

$$\Delta f = \Delta f_p + \Delta f_o + \Delta f_f + \Delta f_g \tag{3}$$

in which

Δf_p = free energy due to hydrostatic pressure
Δf_o = free energy due to osmotic pressure
Δf_f = free energy due to adsorptive force field
Δf_g = free energy due to gravitational force field

In the case of a highway subgrade, the moisture content which may have significant effects upon its stability is great enough that the influence of the adsorptive force fields around the soil particles is probably negligible. Also, osmotic pressure will not be important in subgrade moisture studies except possibly in regions of high soil alkaline content. Therefore, equation (3) may be written

$$\Delta f = \Delta f_p + \Delta f_g \tag{4}$$

When the moisture in a soil column comes into equilibrium with a water table below under isothermal and isobaric conditions, Δf is constant and has the same value at all points. Hence

$$\Delta f = \Delta f_p + \Delta f_g = c \tag{5}$$

Then

$$\frac{d\Delta f_p}{dh} = \frac{-d\,\Delta f_g}{dh} = -\lambda g \tag{6}$$

and

$$\Delta f_p = -\lambda g h \tag{7}$$

in which

h = the height of a point above a free water surface
λ = the density of pure water
g = the gravitational constant

Thus it is shown that the free energy, i. e. , the capillary potential or pressure potential of soil moisture under isothermal and isobaric conditions, is dependent only on the height above a free-water surface and is independent of texture or grain size, state

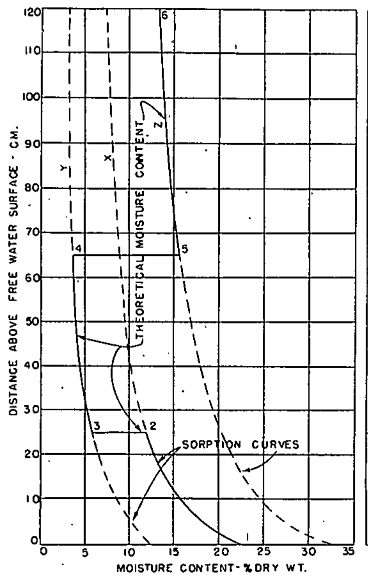

Figure 1.

of packing or density, wetting angle, etc. However, the moisture content of soil at a given height is dependent upon all these factors. Therefore the moisture in different kinds of soil at the same height above a water table must adjust itself so that the capillary potential is a constant value corresponding to that height.

From the above considerations it is concluded that when the capillary moisture in a stratified soil is in equilibrium with a water table, that is, when there is no tendency for upward or downward movement of the capillary water, the moisture content just above and just below the interface between the two soil strata may be considerably different, depending upon differences in character of the two soils. In other words, the theory indicates that the moisture content of a stratified soil undergoes a marked and abrupt change at the interface between strata. It may abruptly increase or decrease depending upon the relative character of the soils involved.

If the sorption characteristics, that is, the relationship between moisture content and capillary potential of the soils are known, the requirement shown by equation (7) indicates that the variation in moisture content upward from a water table will be in accordance with a composite curve consisting of segments of the sorption curves of the soils involved. For example in Figure 1, let curves x, y, and z represent the moisture-capillary potential relationships of three soils X, Y, and Z in stratified arrangement as shown at the right of the diagram. When capillary moisture in this stratified soil is in equilibrium, the broken curve 1-2-3-4-5-6 represents the distribution of capillary moisture throughout the vertical column. This broken curve is made up of segments of the soil sorption curves within the vertical distances corresponding to the thicknesses of the various strata.

In order to verify the above theory, two columns of stratified soils were placed in 4.9-cm. diameter glass tubes and the lower ends of the tubes were immersed in a vessel of water which was open to the atmosphere. After a period of time sufficient for the establishment of quasi-equilibrium had elapsed, the moisture contents of the soils were determined at points about 5 cm. apart throughout the height of the columns. These moisture contents were plotted against height and compared with the sorption curves obtained for the soils by means of a soil tensiometer (3).

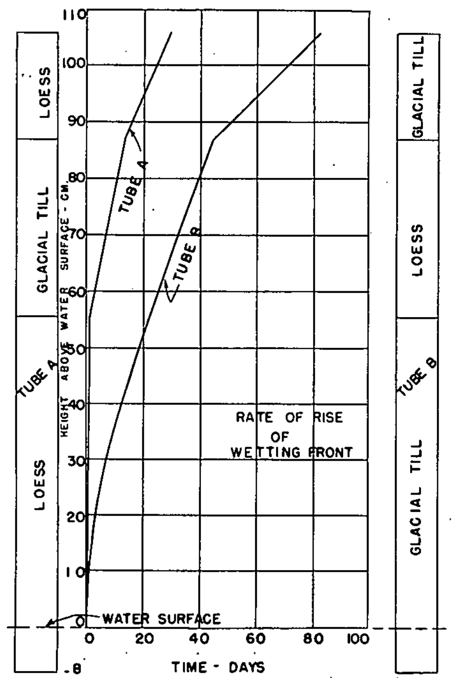

Figure 2.

TABLE 1

Property	Glacial Till	Loess
Location	Story Co., Iowa	Grundy Co., Iowa
Textural classification	Clay loam	Silt loam
BPR classification	A-6 (5)	A-4 (8)
Mechanical analysis		
gravel	6.7%	----
coarse sand	12.1%	0.5%
fine sand	30.2%	18.5%
silt	31.7%	71.5%
clay (5 micron)	19.3%	9.5%
colloids (1 micron)	0.2%	0.5%
Specific gravity	2.69	2.72
Liquid limit	23.4	28.1
Plastic limit	15.4	23.0
Plasticity index	8.0	5.1
Shrinkage limit	12.8	15.5
Proctor density	121.4 pcf.	113.3 pcf.
Optimum moisture content	12.0%	13.5%

One soil used in the tests was a glacial till taken from the C horizon of a Lindley loam deposit near Ames, Story County, Iowa. The sample was taken from a road cut and at an elevation about 12 to 14 ft. below the original ground surface. The other soil was a loess material taken from the B horizon of a Tama silt loam deposit in Grundy County, Iowa. It was taken from the roadside at an elevation about 18 in. below the surface. The properties of these soils are shown in Table 1.

These soils were placed in the glass tubes in three layers and in a different arrangement of layers in each tube. In tube A, the bottom layer consisted of 63.5 cm. of loess; the middle layer, 30.5 cm. of glacial till; and the top layer of 21.5 cm. of loess. In tube B, the bottom layer consisted of 64 cm. of glacial till; the middle layer, 31 cm. of loess; and the top layer of 20.3 cm. of glacial till. The bottom of the soil filled tubes extended 8 cm. below the water surface in the vessel. The soils were air dried and pulverized to pass a No. 10 sieve and then were carefully placed in the tubes in an attempt to maintain uniform density of each of the soils throughout the depth of the layers. The loess soil layers as placed, had a dry density of 93 pcf. and the glacial till 107 pcf. These densities were arbitrarily chosen, but they approximately represent the natural densities at which the soils existed in nature. The bottoms of the tubes were covered with 200-mesh screen held in place by perforated brass plates clamped to the tubes.

After the tubes were filled with soil, the lower ends were immersed in water contained in a bucket. The level of the water surface was maintained constant throughout the tests. The tops of the tubes remained open during the early days of the test, while the wetting front was rising, and for a period of several weeks after the wetting front reached the top of the soil column. Later the top of the soil columns were sealed over with paraffin to prevent evaporation, though a small hole was left in the seal in order to maintain atmospheric pressure in the soil air. The soil filled tubes were mounted rigidly to a concrete wall in a basement room during the tests. The temperature in the room was not thermostatically controlled, although the range and rate of temperature change was relatively small. Therefore it cannot be said that the tests were conducted under isothermal conditions, although the deviation from that ideal was not very great.

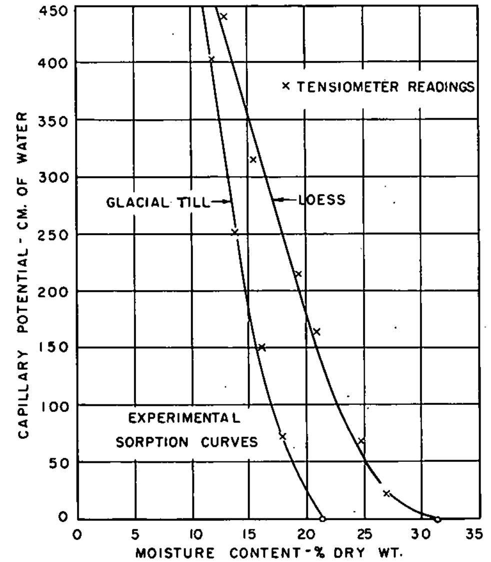

Figure 3.

The rate of rise of the wetting front in each soil column was observed by noting its position daily. These rates are shown graphically in Figure 2. It may be noted that the rate of rise in the upper layers of soil was greatly influenced by the character of the soil layer in contact with the water table. It took the wetting front in tube B, which had a glacial till layer at the bottom, nearly three times as long to reach the top of the column as compared with tube A with loess at the bottom. This result was qualitatively anticipated from the textural character of the two soils.

After the soil columns had been in contact with the free-water surface for a period of approximately 24 weeks, the moisture content of the soils was determined at points about 5 cm. apart throughout their height. In addition, moisture determinations were made at points about 0.5 cm. above and below the planes of contact of the different soil strata. No positive evidence is available to show that the capillary moisture had reached static equilibrium at the time these moisture determinations were made, but in view of the long time which the columns were in contact with water and the short length of columns, the investigators feel reasonably certain that quasi-equilibrium had been established.

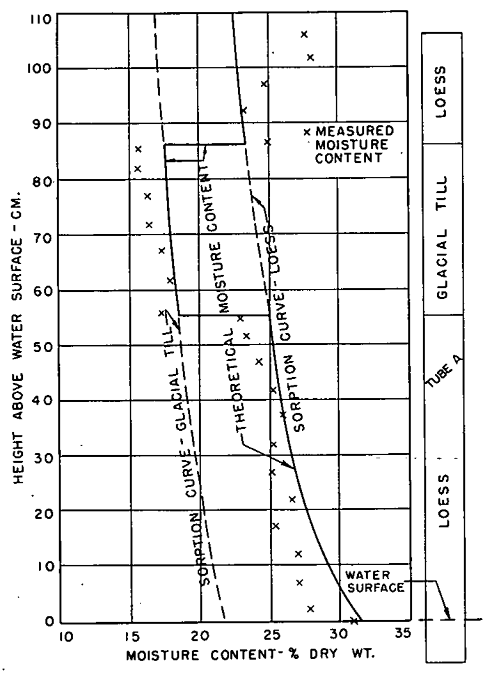

Figure 4.

During the period while the soil columns were standing in contact with water, the capillary potential of the two soils was measured at several different moisture contents by means of a soil tensiometer. These measurements were made with the soils compacted in brass Proctor density molds to the same densities at which they were placed in the stratified columns in the glass tubes. The sorption curves resulting from these capillary potential measurements are shown in Figure

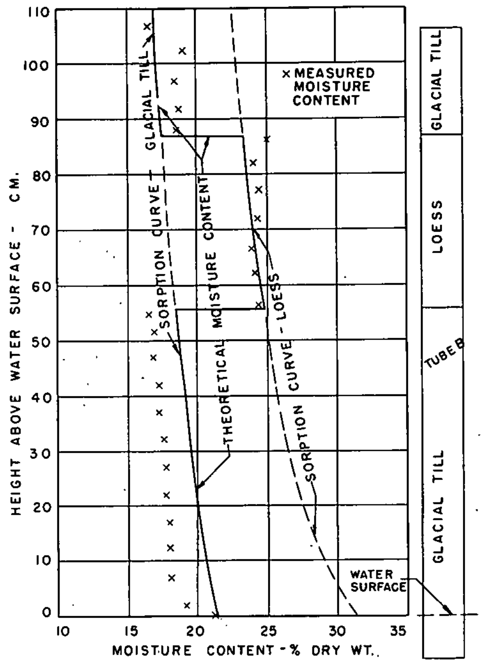

Figure 5.

3. All the points shown on these curves represent actual measured values of capillary potential and moisture content, except the lower terminal points. In these cases the moisture content at saturation was computed from the soil densities and specific gravities. Since it is known that the capillary potential of a soil is zero when it is saturated, the end points of the curves were thus established.

Having obtained the sorption curves for the two types of soil used to make up the stratified columns in the tubes, it was possible to construct theoretical curves for soil moisture versus height above the water surface. These theoretical curves consist of segments of the soil sorption curves corresponding to the thickness of the soil layers in the experimental columns. They are shown in Figure 4 for column A and in Figure 5 for column B. The actual measured values of moisture content at various heights throughout the columns are plotted on these diagrams to show the degree of coincidence between the theoretical and actual moisture contents.

The theoretical and actual values are in reasonably good agreement throughout the height of the soil columns when it is considered that close control of temperature was not exercised during the experiments. It is especially noteworthy that the abrupt changes in moisture content at the interfaces between the various soil strata which are indicated by theoretical considerations were fully developed in the experimental soil columns.

This study indicates that the usual assumption that subgrade soil moisture decreases as height above a water table increases may not always be true, if the soil is stratified. As an example, in Figure 5 it is shown that the moisture content at the water table in the experimental soil column B was something over 21 percent in the glacial till. But in the loess strata extending from 56 cm. to 87 cm. above the water table, the moisture content ranged from 24 to 25 percent.

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