Accumulation of Moisture in Soil Under an Impervious Surface

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The objective of this study was to compare the long-time accumulation of moisture in a soil subgrade beneath an impervious surface with the estimated equilibrium moisture contents based on measurements of the moisture retention characteristics of the soil and the elevation of the groundwater table. Moisture accumulation due to the formation of ice was not considered.

A theoretical approach, based on thermodynamics, was used to evaluate the free energy per unit mass of water in a soil water system in terms of component free energies. Thus, the effects of adsorptive and gravitational force fields, surface tension, pressure and dissolved materials were considered.

The experimental investigation was conducted in two phases. The first phase involved the routine tasks of periodically determining soil moisture contents, soil temperatures and water table elevations under a 150-foot square impervious surface constructed of alternate layers of asphalt roofing paper and asphalt cement. The second phase was conducted to determine the soil moisture retention characteristics, in the form of desorption curves, and other properties of a series of undisturbed soil samples taken from under, and adjacent to, the impervious surface near the close of the field investigations.

EXPERIMENTAL INVESTIGATION

•THE field laboratory site was on the Iowa State University Experimental Farm at Ankeny, Iowa. The parcel selected for the investigation was on a gentle swell of undulating, glaciated land. Drainage in general was quite satisfactory. The glacial till was interspersed with lenses of sand and gravel probably associated with the ground moraine of the Des Moines lobe of the Wisconsin glacier.

Five individual test plots were selected at various positions on the 150-ft sq impervious surface. In addition to the five plots on the surface a sixth (control) plot, supporting normal vegetation, was located approximately 10 ft west of the west edge of the surface (Fig. 1). Each 10-ft sq test plot was marked off with a 1-ft grid system. The intersections of the grid lines were numbered and used as a means of control for routine weekly soil moisture sampling procedures.

The depth of the water table was determined weekly in each of 17 water table tubes and continuously in two 16-in. wells (Fig. 2). Official U. S. Weather Bureau precipitation data are given.

Soil temperatures were determined continuously under the impervious surface and under normal vegetive cover using thermocouples and a 16-point recording potentiometer. The air temperature was determined 1 ft above ground level (Figs. 3 and 4).

As a part of the second phase of this project, a series of undisturbed soil samples in Shelby tubes were taken at the field laboratory. A total of 24 holes were driven, one at each corner of each test plot, using a screw drive mechanism

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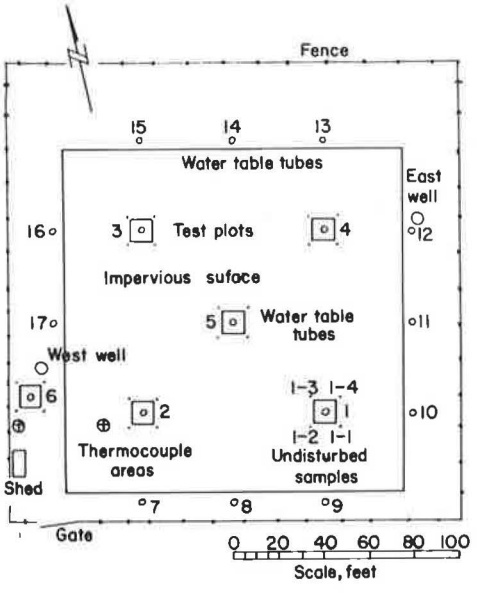


Figure 1. Planimetric layout of the field laboratory.

rather than a drop hammer. Continuous samples were taken in every case to a depth of 10 ft.

In the laboratory, soil physical characteristics were determined for each Shelby tube sample, a total of 170 in all. Desorption curves were determined using individual pressure plate apparatuses. The individual apparatus permitted the determination of an entire desorption curve using a single undisturbed soil sample that was not dislodged from the plate at any time; the entire apparatus was weighed at each pressure. Samples were approximately 2½ in. in diameter by 3 in. high and were saturated prior to the test. Other properties determined were bulk density, Atterberg limits, particle size distribution, textural classification and specific gravity. Composite desorption curves were drawn for all of the 24 test holes (Figs. 5, 6 and 7). The

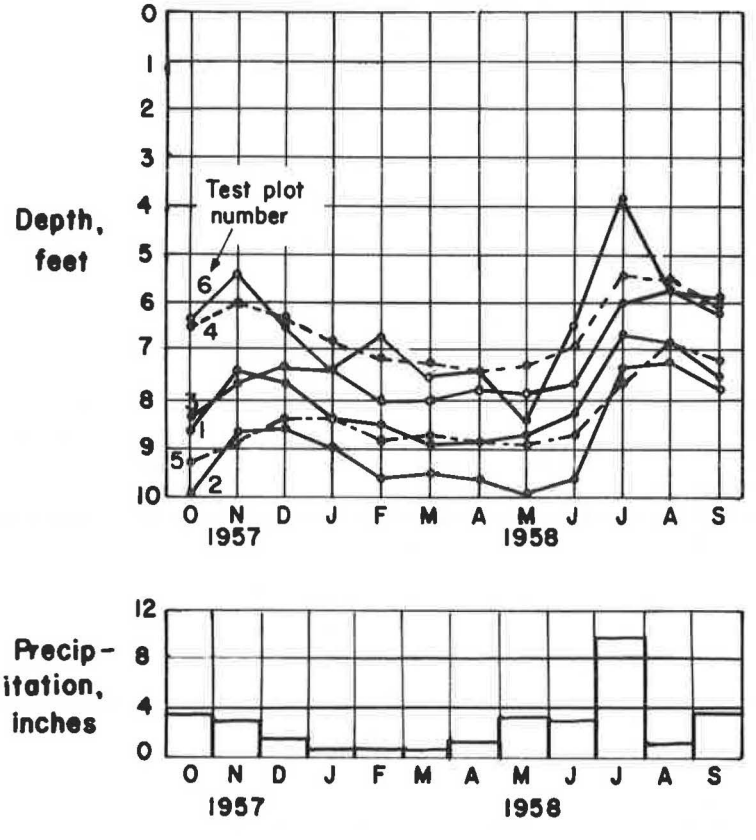


Figure 2. Water table depths and precipitation data.

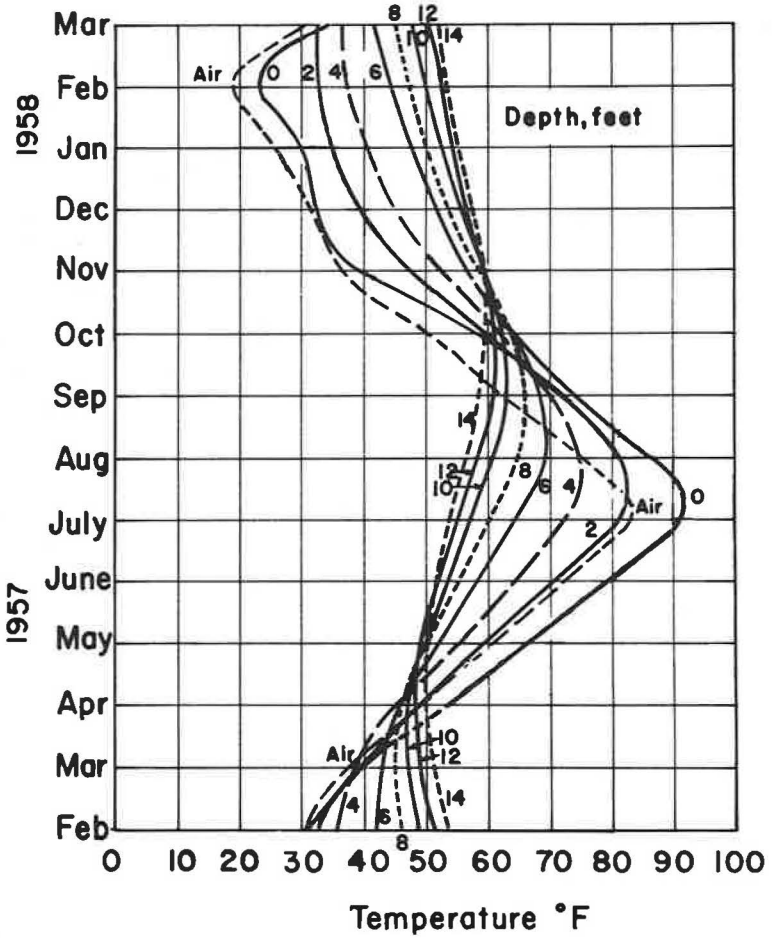


Figure 3. Soil temperatures, covered area.

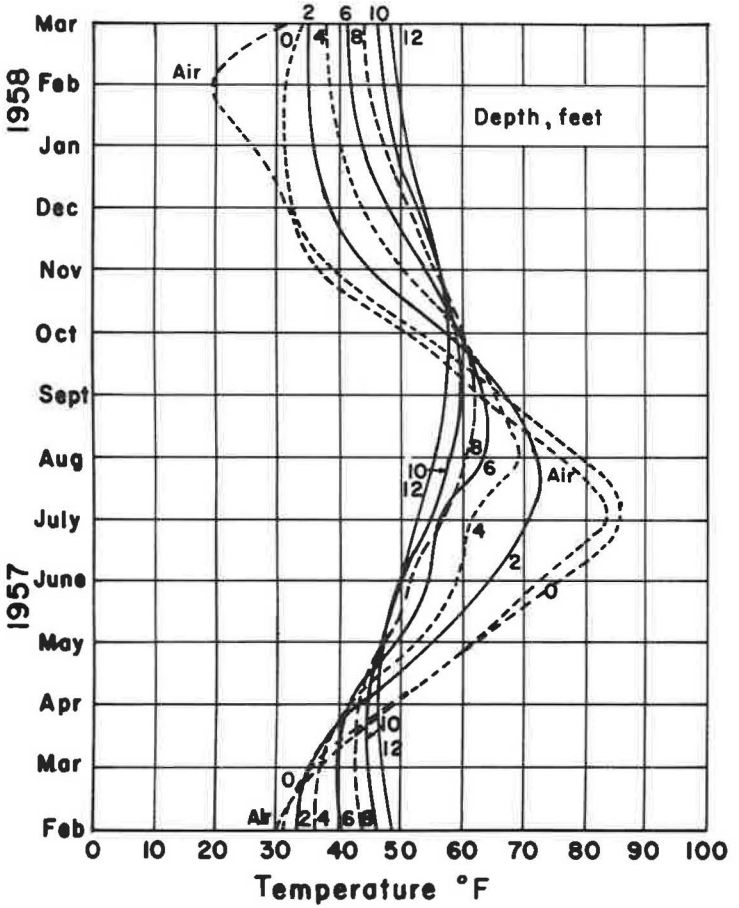
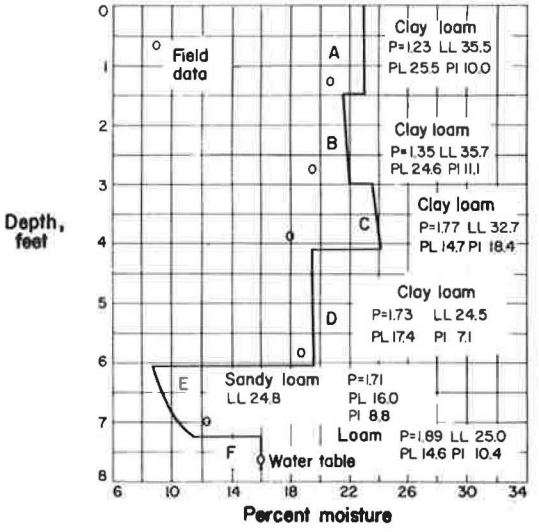


Figure 4. Soil temperatures, control area.



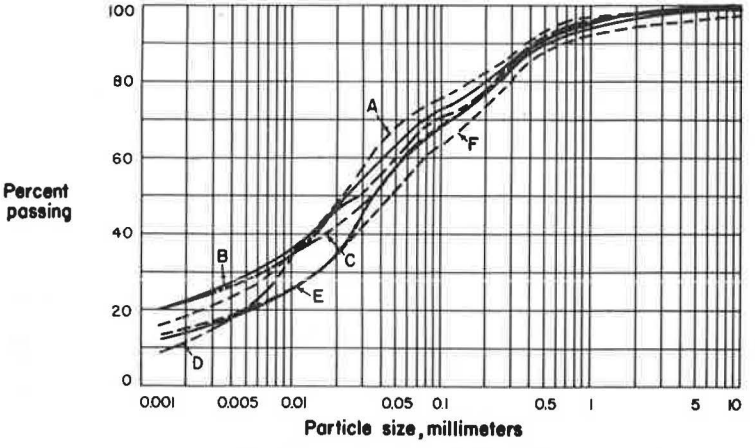


Figure 5. Test hole 1-1. Above: composite desorption curve; below: particle size distribution curves. (In Figs. 5-7 the following symbols are used: P = dry bulk density, PI = plasticity index, LL = liquid limit, NP = non-plastic, PL = plastic limit.)

field data points shown were moisture contents determined when the undisturbed samples were taken.

CORRELATION OF DATA

All soil moisture contents determined during the period October 1957 to September 1958 were tabulated (3). The tabular values were in chronological order and each test plot is listed in numerical order. Originally, direct comparisons of the field data were to be made with the appropriate desorption curves determined in the laboratory. This plan presupposed a somewhat uniform status of the soil types and environmental conditions at the test site. It was later found that such a correlation involved the simultaneous treatment of several salient variables: soil moisture content, soil characteristics, variation of soil characteristics within a given test plot, soil sample depth, water table fluctuation, time and soil temperatures. Since such a comparison was

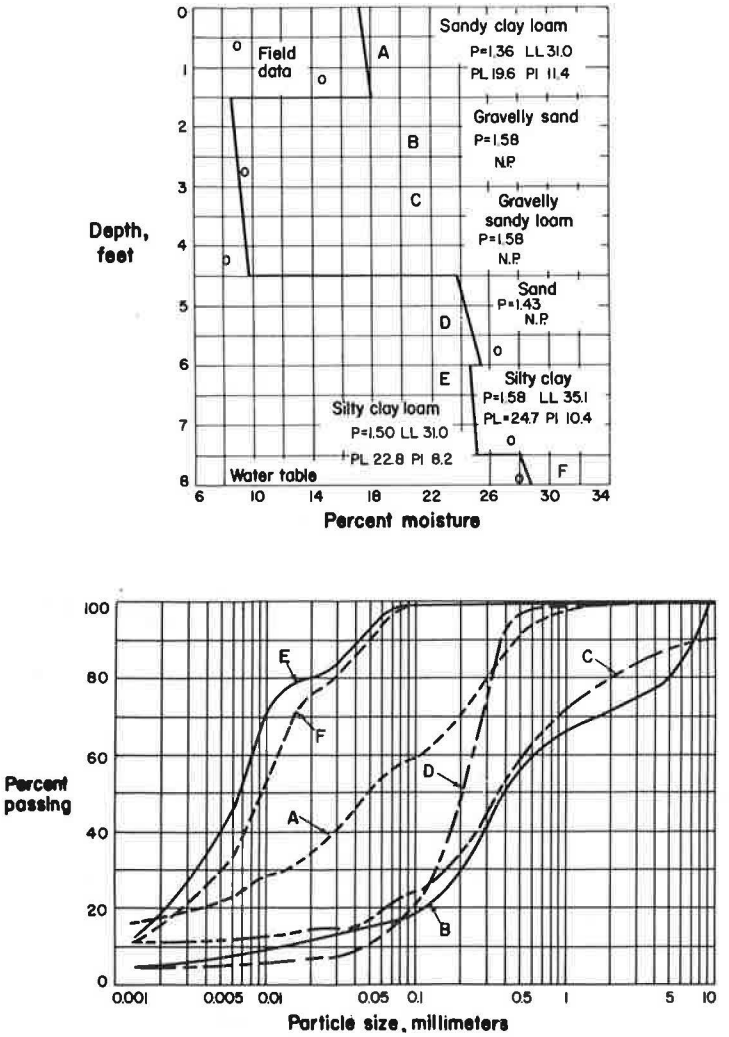


Figure 6. Test hole 2-1. Above: composite desorption curve; below: particle size distribution curves.

virtually impossible, it was necessary to make some assumptions and adjustments in the plan.

The period October 1957 to September 1958 was selected to eliminate water table fluctuation as a variable. During this period water table fluctuations were at a minimum and the individual water table tubes were in full operation.

Time was eliminated as a variable by always assuming an equilibrium condition. Obviously an equilibrium condition was never reached, but the assumption was necessary for simplication.

As a first trial the moisture contents of the undisturbed samples determined at sampling were compared with the desorption curves determined from these same samples. In so doing, a direct comparison was possible because the effect of changing soil characteristics within the test plots was eliminated and because during the sampling period (October 1958) the soil temperatures at all depths were approximately the same. The essentially constant temperatures throughout the soil profile were of the order of 50 F. This phenomenon of constant temperatures at all depths occurs semi-annually as a cyclic temperature "turnover" (Figs. 3 and 4). Since the desorption

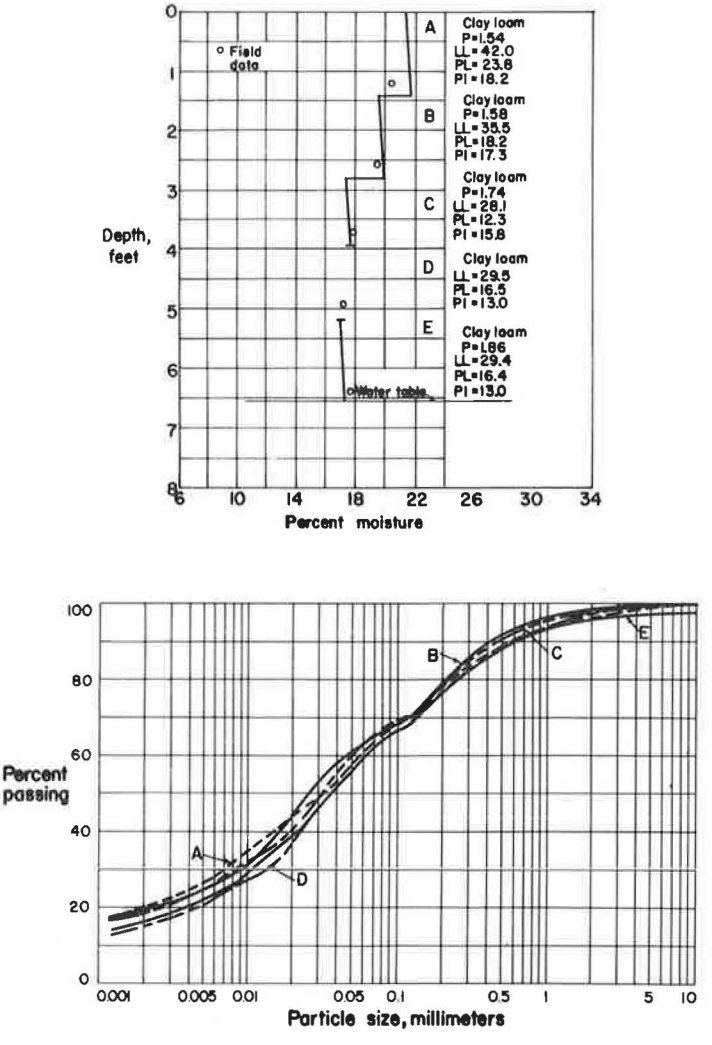


Figure 7. Test hole 6-2. Above: composite desorption curve; below: particle size distribution curve.

curves were determined at a constant temperature of 77 F, the change in moisture content caused by the different temperatures in the field and in the laboratory is probably small. The data are compared with the individual desorption curves (Figs. 5, 6 and 7), and a good correlation exists in nearly every case.

The individual soil moisture contents were too voluminous to use effectively, so it was necessary to determine average monthly moisture contents for each foot of depth for each test plot (Figs. 8 and 9). In most cases, the monthly averages represent four to five weekly moisture contents, although there were fewer determinations in some of the colder months. The moisture content of the upper 2 ft of soil in every test plot fluctuated to a considerable extent throughout the year, but all six test plots exhibited the same trend. This trend showed increasing moisture contents from October 1957 through the colder months of the period and decreasing moisture contents as the warmer months approached. Except for frost on the underside of the impervious surface, no obvious accumulation of ice was encountered. The increasing moisture contents in the upper reaches of the profiles observed during the colder months took place at a time when the water table was falling and the decreasing moisture contents

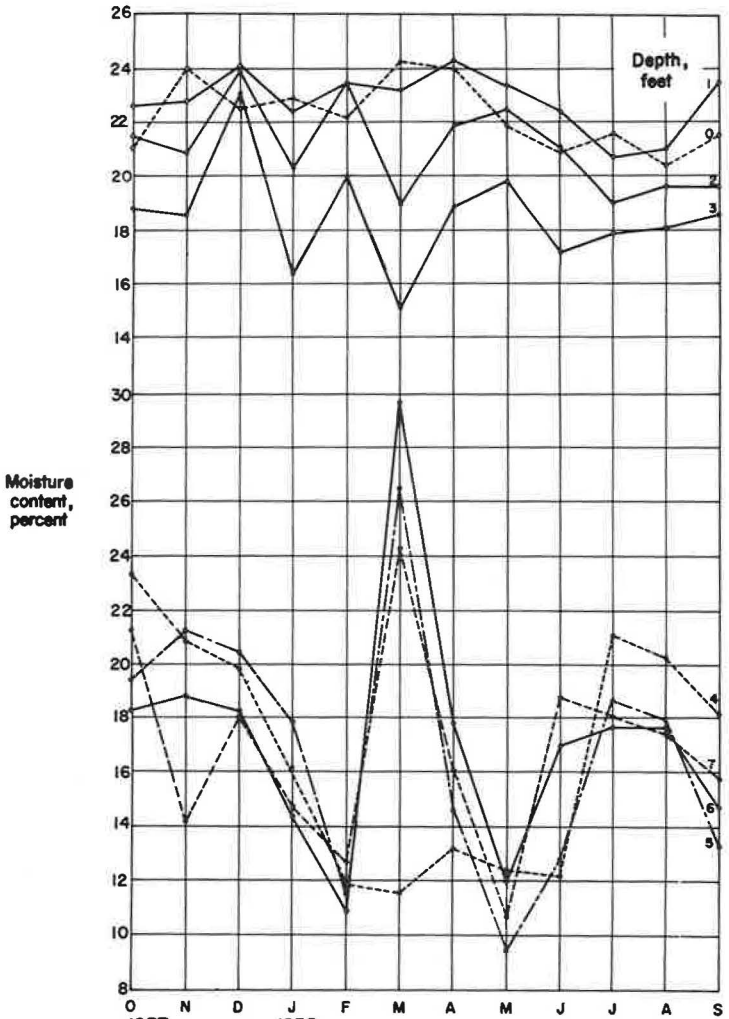


Figure 8. Soil moisture contents, test plot 5.

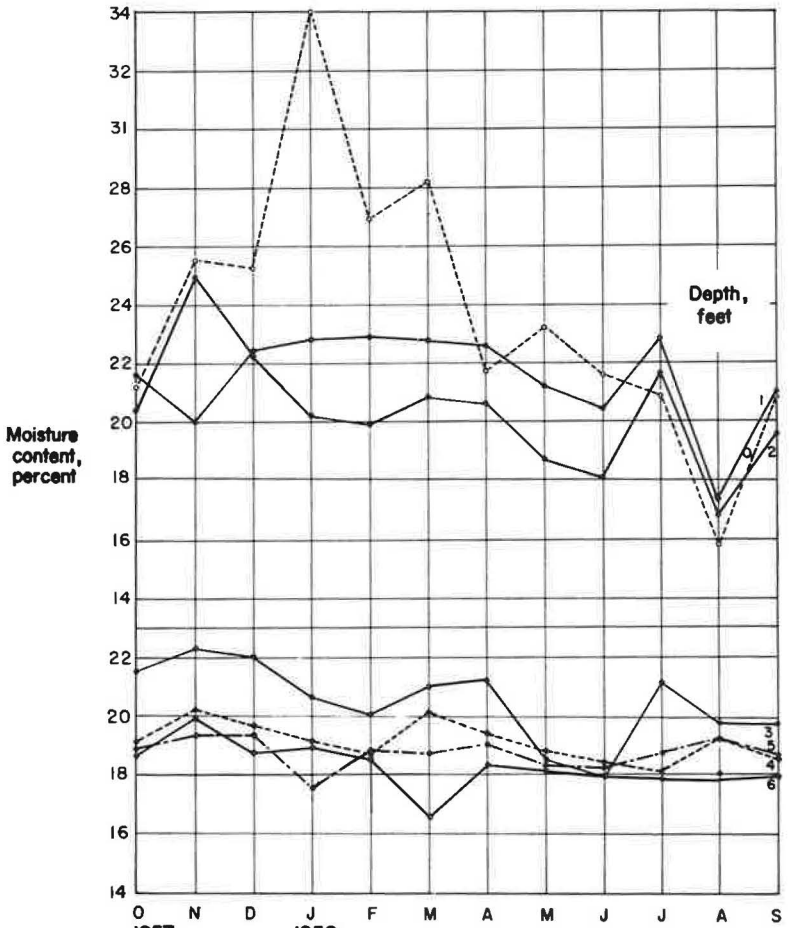


Figure 9. Soil moisture contents, test plot 6.

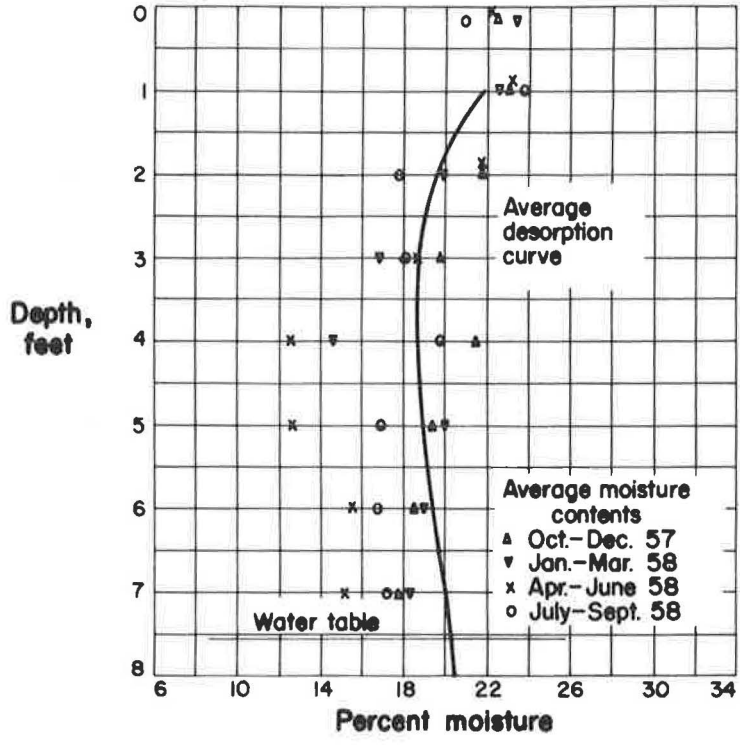


Figure 10. Master desorption curve, test plot 5.

occurring during the warmer months took place at a time when the water table was rising. Most probably this phenomenon was primarily due to changes in soil temperatures.

It was necessary to determine a master desorption curve for each test plot so that a comparison between the field data and the desorption curves could be made, and the difficulties arising from variations of soils within the test plots could be circumvented. In some cases this was done with relative ease, in others with an almost certain loss of accuracy. The four desorption curves of each test plot were given equal weight and averaged. This was done by averaging the moisture contents indicated by the four curves at various depths and then passing a smooth curve through the values obtained. The depths were chosen so they coincided with the depths from which the actual desorption samples were taken.

The weekly moisture contents were averaged for each test plot in three-month periods. These four periods are October to December 1957; January to March 1958; April to June 1958; and July to September 1958. The averages determined for these periods are compared with the six average or master desorption curves (Figs. 10 and 11). By using this system of comparison, the soil moisture contents are expressed in terms of the variables: soil sample depth as expressed as the ordinate, soil characteristics as represented by the sinuosities of the desorption curves, and temperatures as indirectly represented by the four curves determined at different times of the year. The variable resulting from the changing soil characteristics within the individual test plots was accounted for by the averaging process.

APPROXIMATE METHOD FOR PREDICTING MOISTURE CONTENTS FOR DESIGN

The formula for the height of rise in a perfectly wetted capillary may be restated as follows:

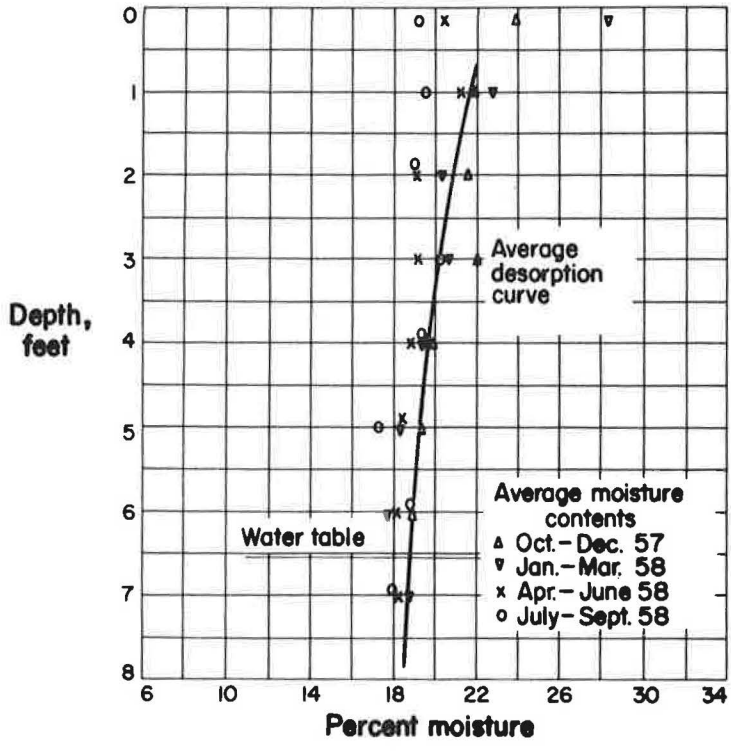


Figure 11. Master desorption curve, test plot 6.

$$\frac{r}{2} = \frac{\sigma v}{gh} \tag{1}$$

where

r = radius of curvature,
σ = surface tension of the water,
v = specific volume of the water,
g = gravitational constant, and
h = height of rise.

The radius of curvature of the menisci at a given position above the datum is not a function of the soil, although the condition of the soil greatly affects the moisture content at a given radius of curvature. Eq. 1 is idealized insofar as the radii of curvature of the menisci are stated in terms of a single radius, r. To generalize Eq. 1, the term r/2 is replaced by a parameter, r_e, which will be referred to as the equivalent radius of curvature:

$$r_e = \frac{\sigma v}{gh} \tag{2}$$

It is now possible to make a plot of the equivalent radius of curvature vs height. There will be a series of such plots, each representing a different temperature.

Now using a desorption curve of a soil under study, it is possible, by making use of a plot of the equivalent radius of curvature vs height calculated for the same temperature which was used to determine the desorption curve, to determine the equivalent radius of curvature for each moisture content of the soil. If the soil is uniform, a statement of the equivalent radius of curvature will then, under equilibrium conditions, indicate the moisture content of the soil.

A change in temperature will change the equivalent radius of curvature at a given height above the datum; the moisture content will then change so that the moisture content is in agreement with the new value of the equivalent radius of curvature. It is therefore possible to predict changes in moisture content which will occur as a result of a temperature change. Note that equilibrium moisture conditions must prevail whenever moisture contents are determined.

The method for predicting moisture contents as given is referred to as an approximate method because: first, the equivalent radius of curvature is an idealized parameter; and second, equilibrium, as such, probably never will be established.

CONCLUSIONS

At the outset of this investigation a preliminary survey was made to determine the logical site for constructing the impervious surface. Many possible sites were rejected because of gravel deposits, poor drainage or for other reasons. The selected site, as it turned out, had some advantages and disadvantages not foreseen; specifically, there existed a wealth of soil types in a small area and a wide range of soil densities were encountered.

The stratified materials encountered were an advantage because their effect on the desorption curves could be studied. Unfortunately, since the stratified materials were not uniform, additional problems were encountered in correlating the data. Occasional marked offsets were observed in the composite desorption curves; many of these were caused by changes in soil types. It is noted that a soil with a very high moisture content may be in equilibrium with an adjacent soil type with a very low moisture content. This is, of course, caused by the differences in the physical and chemical makeup of the soils. In the moisture tension range investigated, the physical characteristics of the soil probably have more effect on the moisture contents than do the chemical characteristics. The data support the conclusion that within a soil column the equilibrium moisture content of a given soil at a given moisture tension, as predicted from its sorption curve, is unaffected by stratification within the soil column (6).

It was not realized, at first, that the equilibrium moisture content of a given soil at a given moisture tension was so greatly affected by its dry density. For this reason, the soil chosen to be covered by the impervious surface was not comparable with the soil that would normally be found under a highway pavement; the density of the soil under a pavement would be greater, no doubt, and more uniform. Actually the changes in density, although introducing additional problems in correlation, were advantageous because their effect on the desorption curves was enlightening. Of particular interest is the apparently reversed trend of the composite desorption curves. For example, where there were no changes in soil type the moisture content increased with increasing height above the water table (Fig. 7). This trend is supported both by the composite desorption curves determined in the laboratory and by soil moisture contents measured in the field. Although other factors may contribute, the explanation for this behavior seems to lie in the changing soil densities. The particle size distribution curves (Fig. 7) do not indicate any appreciable differences in the mechanical analyses of the various components of the soil column. It seems, therefore, that the changing densities are caused merely by greater compaction. Apparently increased compaction changes the pore structure so that, over the range of moisture tensions investigated, the more dense form of a given soil is incapable of holding as much water at a given moisture tension as a less dense form of the same soil. Although the example cited is a special case, the above phenomenon occurs in most of the composite curves to a greater or lesser extent.

The temperature of the soil mass has only a relatively small effect on the equilibrium moisture content. This statement applies only to those ranges of soil moisture tension and temperatures investigated in this project, but the information gathered does support data presented by others (7). This observation does not include the moisture concentrations due to frost action, but only the accumulation due to the temperature differential itself.

The average moisture content at zero depth under the impervious surface in each of the test plots for the period January to March was found to be about 4.5 percent higher than the corresponding average moisture content for the period July to September (Fig. 10). Specifically, test plot number one had an average cold weather moisture content at 21.5 percent and a warm weather moisture content of 17 percent, both at zero depth. Using the proposed approximate method for estimating the change in moisture with temperature, it is found that the method estimates a change of 15 percent or a reduction of 3.3 percent moisture content from the cold period to the warm period. The 4.5 percent figure compares favorably with the 3.3 percent figure when it is considered that frost accumulation during the winter is ignored and that the average temperatures at zero depth do not reflect the true picture of the extremes; temperatures directly beneath the impervious surface were measured in excess of 120 F. Such a high temperature probably would not be possible under a pavement slab because of the thickness of the pavement as opposed to the very thin impervious layer employed in this project.

The findings of this investigation may be summarized as follows:

1. The equilibrium moisture contents in a soil column under an impervious surface can be predicted from desorption curves run on undisturbed samples of the soils providing that both the temperature and water table elevation are known.
2. Temperature has only a minor effect on the ultimate moisture contents predicted, except under extreme temperature conditions. The temperatures measured directly beneath the impervious surface during this investigation were considered to be abnormally high during the summer months and therefore rather large changes in moisture content resulted.
3. For soils such as were encountered in this investigation, the changes in moisture content attributable to changes in temperature can be predicted within close limits with the approximate method herein proposed.
4. Terminal moisture contents at various depths under an impervious surface as predicted by appropriate desorption curves are not affected by soil stratification.
5. At relatively low moisture tension values soil density has a decided effect on equilibrium moisture contents, higher moisture contents being observed at lower soil densities.
6. Under normal field conditions, where increasing soil density is noted with increasing depth, it is possible to note increasing moisture contents with increasing height above the water table.

By using the results of this study, an engineer could predict the terminal soil moisture contents under an existing or planned impervious surface. To predict the terminal moisture contents, the engineer would have to determine the desorption curves of the soils in the condition in which they occur in the embankment. In a highway pavement structure the soil samples would be compacted to the design density. The engineer would also have to predict the highest level of the water table under the surface and estimate the probable soil temperature. The proposed approximate method estimates equilibrium moisture content changes resulting from temperature differentials. It must be emphasized, however, that this method will not account for moisture accumulation due to "ice lenses," nor would it necessarily be accurate if saline soils were encountered. With this knowledge, the engineer could then determine the bearing capacity of the soil at the predicted moisture content rather than at saturation.

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