Soil-Moisture Properties of Subgrade Soils

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Soil moisture and matric potential are discussed. The soil-moisture-characteristics curve is explained, and typical curves for a variety of soils are presented. These curves are compared, and similarities and differences are emphasized. Civil engineering uses of soil-moisture-characteristics curves are explained, and examples of applications to engineering practice are presented.

Moisture is of primary importance in the performance of a pavement subgrade. The shear strength of soil is very sensitive to change in moisture content. Black (1) has shown California bearing ratio, which is a measure of relative shear strength, to be inversely proportional to moisture content (see Figure 1). Thus, the shear strength of a given subgrade can be expected to vary as moisture content changes with climate.

Thompson (2) found that the dynamic or resilient modulus of unsaturated soils is dependent on moisture content. As the moisture content increased, the resilient modulus decreased and larger subgrade deflections that can cause premature pavement failure were observed. Again, moisture was shown to have a detrimental effect on subgrade performance.

Moisture is a major factor in frost heaving. Taber (3) states that the amount of frost heaving that takes place is limited by the supply of available water. This water can either be already present in the soil or be drawn up from points below the depth of freezing. However, the rate of water flow in an unsaturated soil is controlled by the unsaturated hydraulic conductivity, which decreases substantially with a decrease in moisture content (4). Therefore, moisture content influences frost heaving directly as readily available water and indirectly by affecting the unsaturated hydraulic conductivity.

Just as subgrade-strength properties are important inputs in pavement design, so should moisture content and moisture distribution be important inputs in subgrade-strength evaluation. Although it is generally known what the moisture content of a subgrade is at compaction, the field moisture content after a few years can be completely different. Dempsey (5) and Janssen and Dempsey (6) have listed numerous cases in which subgrade soils under in-service pavements were at other than optimum moisture content. It was found that a significant number of soils with high clay contents were well above optimum moisture content.

Subgrade moisture content is a direct function of climate and seasonal fluctuations in the water table (5). The determination of subgrade moisture content and subsequent subgrade strength for use in design appears to be very complex. A rational approach to the problem of moisture prediction is needed if expected field moisture contents are to be incorporated into pavement design.

STUDY OBJECTIVES

This study was conducted to show how data on soil-moisture characteristics can be determined and used in pavement soils evaluation. The specific objectives were to

1. Define the concepts of matric potential or soil suction;
2. Describe the relation expressed by a soil-moisture-characteristics curve;
3. Compare soil-moisture-characteristics curves for a sand, a silt, and a clay; and
4. Show how the soil-moisture-characteristics curve can be used to estimate soil strength and hydraulic properties.

MOISTURE POTENTIAL

It is not surprising that the moisture content of a compacted subgrade does not remain as compacted at optimum moisture content. There are many energy potentials and boundary conditions that are responsible for water movement in a soil. Gravity potential tries to pull water down to the static water level, or water table. Opposing this potential and trying to keep the water in the soil is the surface tension or matric potential. The gravity potential being opposed by the matric potential is shown by the following equation:

$$H = Z + h \quad (1)$$

where

H = total soil-moisture potential or total head,
Z = gravitation potential or position head, and
h = matric potential or pressure head.

When $H = 0$, there is no moisture movement and equilibrium exists. The matric potential is then equal to the negative of the gravity potential.

Matric potential is often visualized as a suction exerted by the soil to pull water up from the water table. This suction is dependent on the soil pore geometry or soil matrix--thus, the term matric potential. The concept of matric potential is easier to understand if an analogy is made between the pores in the soil and capillary tubes (see Figure 2). Water in a narrow tube will rise above

Figure 1. CBR versus moisture content at various dry densities.

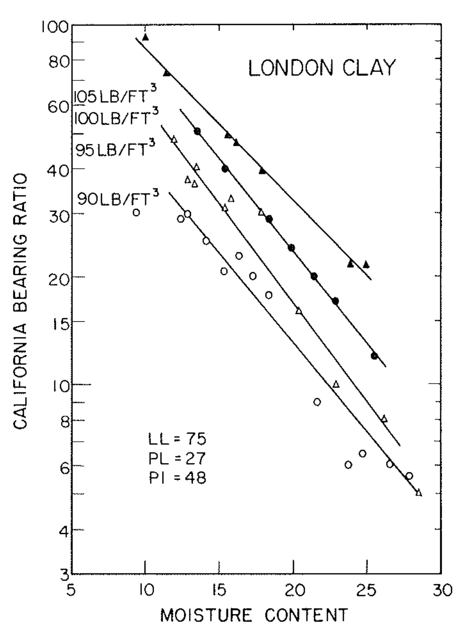


Figure 2. Capillary tubes showing air-water interfaces at different radii of curvature.

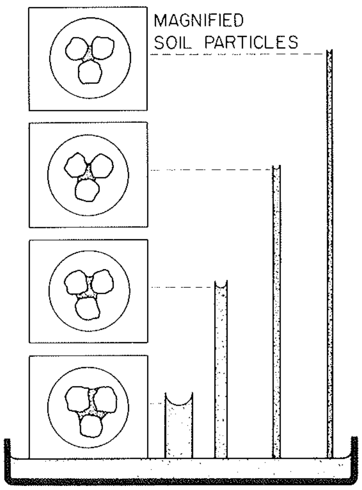
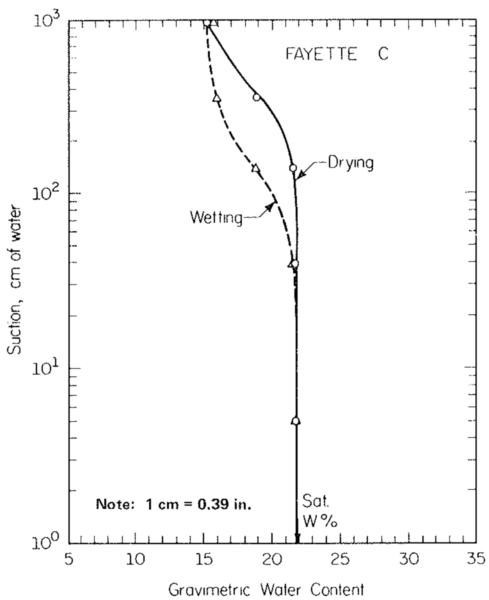


Figure 3. Typical soil-moisture-characteristics curve.



the free-water height until an equilibrium condition is reached. The water in the tube forms a meniscus at the air-water interface that is approximately semicircular in shape and is called the radius of curvature. The smaller the radius of curvature, the higher the water will rise in a capillary tube. A similar meniscus and radius of curvature can form in the water between soil particles. The height of capillary rise can be described mathematically by the following equation:

$$h = (2\sigma \cos\alpha/\gamma_w g r) \quad (2)$$

where

- h = height of capillary rise,
- σ = surface tension of water,
- α = contact angle between the wall of the tube and the surface of the water,
- γ_w = unit weight of water,
- g = acceleration of gravity, and
- r = radius of the tube.

It is the surface tension of the water acting on the walls of the tube that is holding the water above the free water level.

If soil samples at the free water level were examined, they would be found to be effectively 100 percent saturated. If the water table were lowered, the degree of saturation would be found to decrease. This is according to Equation 2, which indicates that the larger pores would not have sufficient energy potential or suction to hold water as the height above the water table increased.

SOIL-MOISTURE-CHARACTERISTICS CURVE

A graph showing decreasing degree of saturation or water content with increasing matric potential is very useful in pavement engineering, where unsaturated soil strength and behavior are important. Such a graph is called a soil-moisture-characteristics curve. A convenient form of the graph has water content on the horizontal axis and the logarithm of matric potential on the vertical scale (see Figure 3). The logarithmic scale for matric potential is used to cover a larger range of suction values while still providing good detail at low values of suction. It should be noted that the graph in Figure 3 consists of two curves: (a) a drying or desorption curve and (b) a wetting or sorption curve. Because of the complex nature of soil pore structure, a different curve is obtained depending on whether the soil is being wetted or dried. This difference is known as hysteresis. Various explanations for moisture hysteresis can be found in the literature (7). Generally, the drying curve is sufficient for most civil engineering uses.

The relation expressed in a soil-moisture-characteristics curve is a soil property that is of fundamental importance in the analysis of moisture equilibrium and flow behavior in soil. Physically, the curve tells (at any given moisture content) how much energy (per unit quantity of water removed) is required to remove a small quantity of water from the soil. Janssen and Dempsey (6), Hillel (7), Taylor and Ashcroft (8), Kirkham and Powers (9), and Rose (10) have presented detailed explanations of how water is held in soil, and Childs (11) has considered in great detail the mechanisms by which water is held in both swelling and nonswelling soils.

The soil-moisture-characteristics curve can also be used to predict unsaturated hydraulic conductivity (4). Elzeftawy and Dempsey (12) have used soil-moisture-characteristics data along with measurements of saturated hydraulic conductivities (permeabilities) to predict unsaturated hydraulic conductivities for highway soils. Although this can be used for complex transient moisture modeling, there can also be simplified applications to civil engineering problems (12).

Croney and others (13) have described the methods used to determine the soil-moisture-characteristics curve. Generally, these methods consist of the tensiometer method, the direct suction method, the pressure-plate method, and the centrifuge method. Usually, no single method can be used to cover the entire range of moisture tension. Thus, several measurement methods may be used in actual practice.

Figure 4 shows a simple type of tensiometer system that can be used for the low moisture-tension range [<100 kPa (<1 bar)]. The apparatus shown in Figure 4 consists of a porous plate with its pores filled with water. The chamber beneath the porous plate is filled with water and connected to a flexible tube that is also filled with water. The negative head or matric potential is equal to the distance h between the soil sample and the outflow end of the flexible tube in Figure 4. The soil-

Figure 4. Tensiometer system.

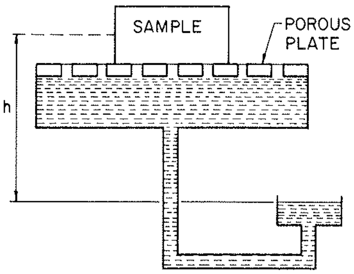


Figure 5. Testing cell with pressure coupling.

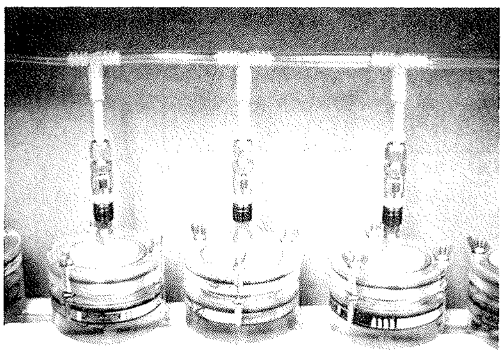
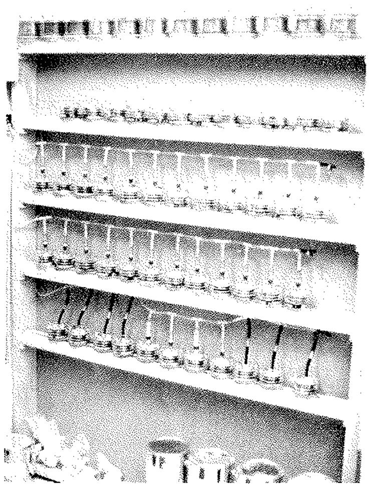


Figure 6. Testing-cell setup.



moisture-characteristics curve is determined from the relation between the water content of the soil sample and the magnitude of the negative pressure head of the water.

Figure 5 shows a practical laboratory testing cell that holds a sample weighing about 100 g. Pressure rather than suction is applied to the sample through a connecting tube on the top of the cell. The pressure is controlled by a regulator and measured with a mercury manometer. This cell can be used for pressures up to 100 kPa (1 bar). A large number of cells can be put in a relatively small amount of space (see Figure 6). A pressure-plate system is used for the high pressure range--i.e., up to 1500 kPa (15 bars). A detailed description of the testing procedure may be found elsewhere (6).

A useful simplification occurs when the soil suction or matric potential is given in units of water head. A suction of 20 cm (0.6 ft) will lift a column of water 20 cm above a free water surface. Therefore, the suction on the moisture-characteristics curve can be equated to the distance above a water table for equilibrium conditions. In addition, by use of the soil-moisture-characteristics curve, it is possible to estimate the equilibrium moisture content at various positions above the water table.

COMPARISON OF CURVES

A comparison of typical soil-moisture-characteristics curves for a sand, a silt, and a clay--shown in Figures 7, 8, and 9, respectively--indicate interesting differences. In Figure 7, the sand [at a density of 1774 kg/m^3 (110 lb/ft^3)] shows a definite decrease in moisture content over the low matric-suction range, and it has a tendency to approach a constant moisture content at the higher suction values. It should be noted that the total change in moisture content over the suction range is large and a moisture content of less than 5 percent is reached at about 400 cm (13.1 ft) of head. The sand loses water readily at the lower suction values because of its greater percentage of larger pore sizes.

In Figure 8, a Hosmer silt soil [classification A-4, with a density of 1530 kg/m^3 (94.9 lb/ft^3)] shows a tendency to remain near the saturation moisture content until a suction head of about 100 cm (3.3 ft) is reached. The silty soil then shows a rather large decrease in moisture content as the suction increases beyond 1000 cm (32.8 ft) of head.

The Bluford clay soil in Figure 9 [classification A-7-6, with a density of 1705 kg/m^3 (105.7 lb/ft^3)] tends to display a gradual and uniform decrease in moisture content as the matric suction increases. It is the distribution of pore sizes in a soil that is responsible for the shape of the soil-moisture-characteristics curves noted for the different soil types.

It is important to note that the silty soil in Figure 8 and the clayey soil in Figure 9 do not reach optimum moisture content until a matric suction greater than 1000 cm (32.8 ft) is reached. Therefore, for equilibrium conditions, when there is no tendency for vertical water movement, water contents above optimum should be expected in Hosmer and Bluford soils when a shallow water table exists.

The shape of the soil-moisture-characteristics curve is important in relation to the sensitivity of a soil to changes in moisture content. It is observed in Figure 8 that the suction of the Hosmer silt soil decreases substantially with a small increase in moisture content. The Bluford clay soil shows less decrease in suction for a similar increase in moisture content. Since strengths of unsaturated soils are directly related to matric suction, it would appear that strength changes in Hosmer silt would be greater than those in Bluford clay for similar changes in moisture content.

APPLICATIONS TO ENGINEERING PRACTICE

Thompson and Robnett (14) developed a relation for determining the resilient modulus of soil by using volumetric water content in the following linear regression equation:

$$E_{ri} = a + b\theta \quad (3)$$

Figure 7. Soil-moisture-characteristics curve for Torpedo sand.

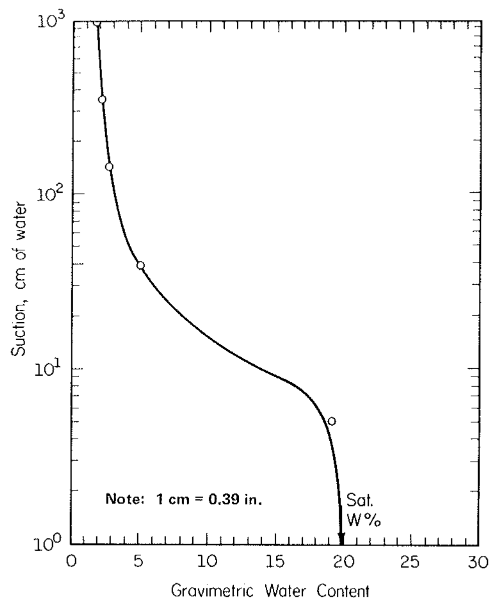
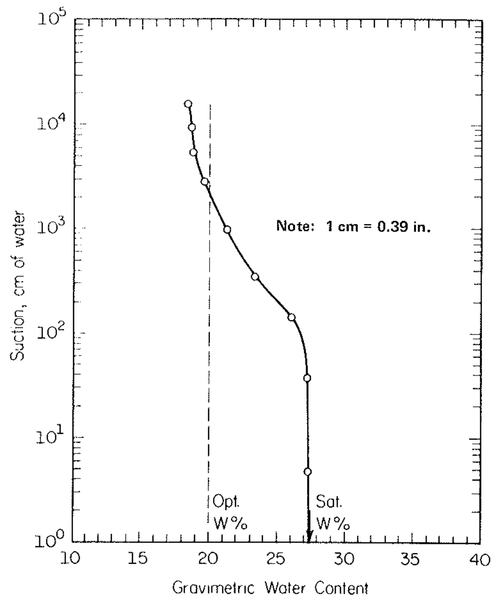


Figure 8. Soil-moisture-characteristics curve for Hosmer A silt.



where

Eri = resilient modulus ($kips/in^2$),
a and b = regression constants, and
θ = volumetric moisture content, given by

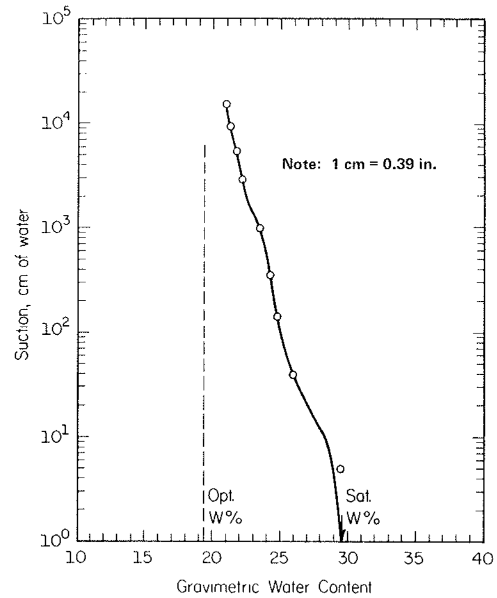
$$\theta = w(\gamma_d/\gamma_w) \quad (4)$$

where

w = gravimetric moisture content,
γ_d = dry unit weight of soil, and
γ_w = unit weight of water.

For B- and C-horizon soils compacted to 95 percent AASHTO T-99 density that have dry densities less than or equal to 1600 kg/m^3 (100 lb/ft^3), a is

Figure 9. Soil-moisture-characteristics curve for Bluford B clay.



27.06 and b is -0.524. For B- and C-horizon soils at 95 percent density that have dry densities greater than 1600 kg/m^3, a is 18.18 and b is -0.404 (14).

By using Equation 3 and the soil-moisture-characteristics curve, it is possible to estimate the resilient modulus of subgrade soils in the field for equilibrium moisture conditions. The procedure is demonstrated in the following examples.

Example 1

The resilient modulus of a Hoyelton B subgrade soil compacted at 1442 kg/m^3 (90 lb/ft^3) is to be determined. The Illinois Department of Transportation Soils Manual (15) indicates that the water table varies from 30 to 92 cm (1-3 ft) from the surface during the year. The soil-moisture-characteristics curve in Figure 10 for Hoyelton B soil [classification A-7-6, with a density of 1442 kg/m^3 (89.4 lb/ft^3)] shows that the equilibrium moisture content for a matric suction of 30 cm (1 ft) is 30.5 percent. By putting the appropriate data into Equation 3, the following resilient modulus is obtained: Eri = 27.06 - 0.524 (30.5) (90/62.4) = 4.0 $kips/in^2$.

Example 2

It may be of interest to determine the effect of lowering the depth of the water table to 122 cm (4 ft) on the resilient modulus of Hoyelton B by use of deeper ditches. For a matric suction of 122 cm, the equilibrium moisture content is 28.0 percent and the resilient modulus is as follows: Eri = 27.06 - 0.524 (28.0) (90/62.4) = 5.9 kips/ in^2. The resilient modulus is increased about 48 percent by lowering the water table 92 cm (3 ft).

Example 3

Elliot B and Hoyelton B soils are to be considered for use as borrow material for subgrade construction. Both soils are expected to require drying to reduce the moisture content to optimum. It is desired to determine which soil will dry to optimum

Figure 10. Soil-moisture-characteristics curve for Hoyelton B soil.

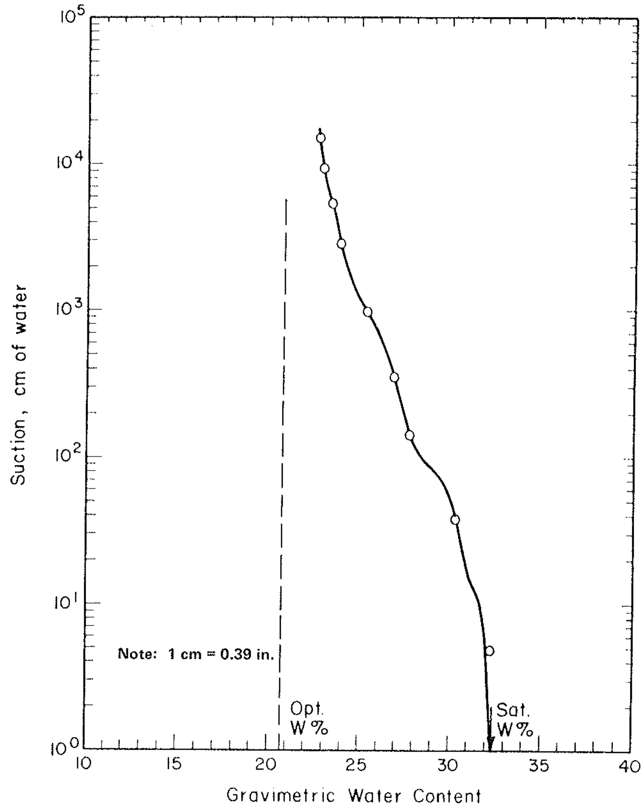
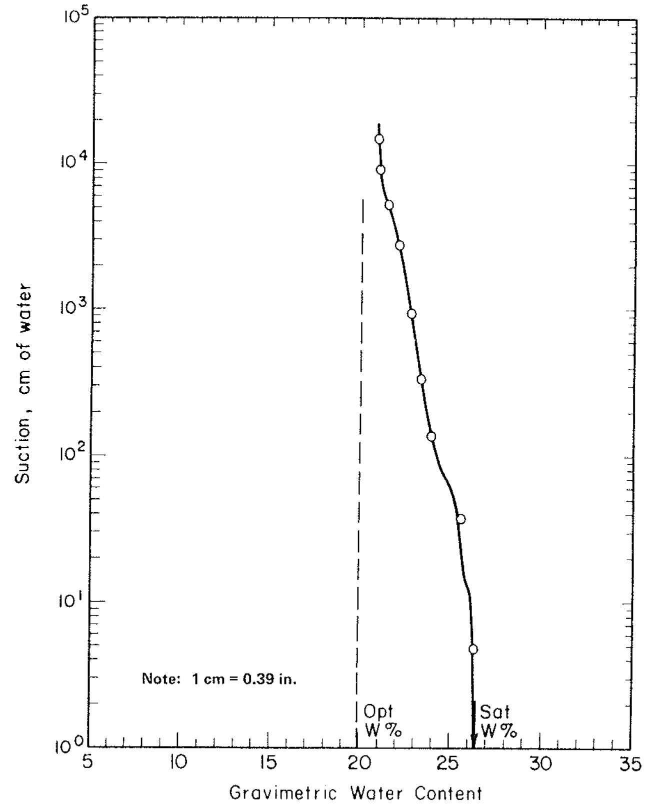


Figure 11. Soil-moisture-characteristics curve for Elliot B soil.



moisture content the quickest for field compaction. From Darcy's law,

$$q = -K(\theta)\nabla H \quad (5)$$

where

q = moisture flux;
K(θ) = hydraulic conductivity, which is a function of moisture content; and
∇H = hydraulic head gradient, which may include both matric suction and gravitational components.

It is shown that the flux (q) is a function of the unsaturated hydraulic conductivity [K(θ)] and the energy gradient (∇H). If it is assumed that both soils will display similar energy gradients through the aggregate particles as pulverization occurs, then the moisture flux or drying rate will be directly proportional to the hydraulic conductivity, which varies as water content decreases. If the soils are at optimum moisture content plus 5 percent at the start of the drying process, the average moisture content when the soils are 50 percent dried would be optimum plus 2.5 percent. For Hoyelton B in Figure 10, this is 23.2 percent; for Elliot B in Figure 11 [classification A-7-5, with a density of 1605 kg/m³ (99.5 lb/ft³)], it is 22.4 percent.

Figures 12 and 13 show hydraulic conductivity versus moisture content for these two soils. From these graphs it can be seen that the unsaturated conductivity for Hoyelton B at a moisture content of 23.2 percent is 2×10^{-12} cm/s; for Elliot B at a moisture content of 22.4 percent, the hydraulic conductivity is 1×10^{-9} cm/s. As $(1 \times 10^{-9})/(2 \times$

Figure 12. Hydraulic-conductivity curve for Hoyelton B soil.

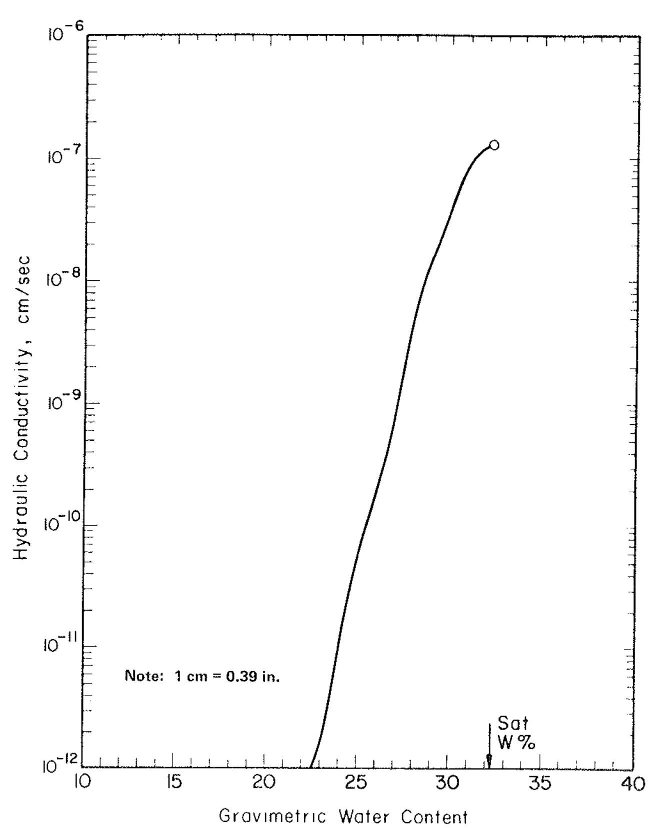
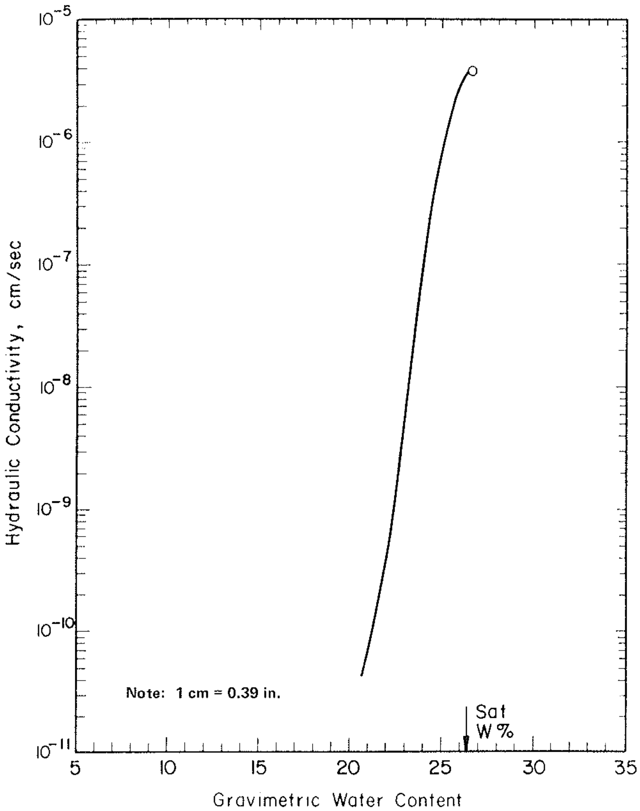


Figure 13. Hydraulic-conductivity curve for Elliot B soil.



10^{-12}) = 500, then Elliot B would be expected to have a moisture flux about 500 times greater than that for Hoyelton B and would be expected to dry considerably faster.

A detailed description of the engineering properties for the soils used in this paper, along with soil-moisture-characteristics curves for other soils, may be found elsewhere (6).

CONCLUSIONS

From the results of this study, the following conclusions are presented:

1. The performance of a pavement subgrade depends greatly on subgrade moisture content because of its influence on subgrade strength. By using the soil-moisture-characteristics curve for the particular soil and knowing the depth to the water table, the equilibrium moisture content of the soil can be predicted.
2. The soil-moisture-characteristics curve can be helpful in identifying soils that are susceptible to large changes in moisture content as a result of changing boundary conditions.
3. The soil-moisture-characteristics curve can be used to predict unsaturated hydraulic conductivity as a function of moisture content, which is useful in predictions of transient moisture content and frost susceptibility and in evaluations of subgrade compaction.
4. The soil-moisture-characteristics curve provides important information about moisture held in the soil and is an important aid in the evaluation of soil and material strength for the design of pavement systems.

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The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Illinois Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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Volume Changes in Compacted Clays and Shales on Saturation

R.A. ABEYESEKERA AND C.W. LOVELL

The midwestern United States has only a limited quantity of so-called swelling soils. However, substantial volume changes may occur in the compacted clay and shale embankments of the area as they become saturated in the service environment. Since these deformations are likely to be the greatest these embankments will ever experience, their prediction and control are of considerable practical interest. To aid in the accomplishment of this important engineering objective, the results of an extensive study of these volume changes for laboratory-compacted clays and shales are reported (the study is being extended to field-compacted clays). Saturation was accomplished under high back pressures, for either triaxial or consolidation samples, and confinement simulated various embankment positions. The volume changes that resulted could be either increases (swell) or decreases (settlement), depending on the level of confinement and the compaction variables. From such testing, statistically valid prediction equations were derived in terms of (a) the compacted density or void ratio, (b) the water content or degree of saturation, and (c) the confining pressure. These equations show how the volume changes on saturation can be controlled by appropriately altering the details of the compaction specification.

Compacted clays and shales are used in large quantities in the construction of earth embankments and other fills. Ensuring the stability of these structures against a slope failure is always of major concern, and in most cases it is the sole criterion taken into consideration in actual design, which is unfortunate.

The compressibility and swelling characteristics of compacted soils and shales, particularly over the long term, must also be taken into consideration in the design phase. These volume changes are dependent on the compaction variables--e.g., water content, dry density, method of compaction, and soil and/or shale type--and on the confining pressure under which the fill absorbs water. A soil or shale compacted to a high density and confined under a relatively low pressure will tend to swell on saturation. On the other hand, a low-density soil or shale under a relatively high confining pressure will tend to compress on saturation. Under certain conditions, a soil or shale may not change in volume at all on saturation.

Accordingly, it is clear that it is extremely difficult, if not impossible, to design an earth fill to avoid volume changes in the completed structure. The most one can do is to place the fill in such a condition that the cumulative effects of the differential volume changes are within "acceptable" limits. To achieve no volume change on saturation, one would have to vary the as-compacted condition of the soil or shale over the depth and width of the fill. Although this unconventional approach is theoretically possible, it is extremely difficult to achieve in practice.

This paper discusses the volume-change characteristics of two troublesome fill materials: a highly plastic clay from St. Croix, Indiana, and a medium-hard, nondurable shale from the New Providence formation in Indiana. Statistically derived prediction equations are given in terms of (a) compacted density or void ratio, (b) water content or degree of saturation, and (c) confining pressure for fully saturated samples. These equations show how volume changes on saturation can be estimated and used in the design phase to control the cumulative effects of soil or shale compression and swelling in an earth fill.

LITERATURE REVIEW

Swelling Potential

Various systems have been advanced to define the swelling potential of soils. These systems are based on intrinsic soil properties as well as the properties of soil in a compacted state.

Ladd and Lambe (1) suggested a rating system called potential volume change, which varied linearly with the percentage of heave under a surcharge of 9.5 kPa (200 lbf/ft^2), the plasticity index of the soil, the water content of the soil at 100 percent relative humidity, and the calculated percentage of volume change resulting from drying a saturated sample from the field moisture equivalent (ASTM D426-39) to the shrinkage limit.

Seed and others (2) defined swelling potential as "percentage swell of a laterally confined sample on soaking under [7 kPa] 1 psi surcharge after being compacted to maximum density at optimum moisture content in the standard AASHO compaction test." They found that the swelling potential is a function of the activity of the soil and the percentage of clay size, and they defined the activity of the soil as the rate of change of the plasticity index with clay content rather than the ratio of the plasticity index to the clay content (3).

Kassif and Baker (4) stated that, for a quantitative evaluation of the amount of heave under field conditions, the whole range of volume change under various surcharges is required. They therefore defined swelling potential as the integral of the swell-pressure curve for the range of surcharges representing field conditions.

Kassif and others (5, p. 218) and Krazynski (6) have drawn attention to the numerous and widely different methods that have been proposed and used for testing and classifying expensive soils.

Swelling Behavior

The swelling behavior of partially saturated soils has been studied extensively (1,4-23). The factors that influence swell magnitude include type and