Mr W. H. Campen, *Omaha Testing Laboratories:* On one project we had to do considerable compacting during the night when the temperature was cool Apparently we got fair density and stability during the night, but the next day, when the temperature rose, the stability was less than it was before and tests disclosed higher moisture contents than was expected; that is, higher than the stability would indicate at low temperatures. This incident indicates that more water acts as free water as the temperature rises.

SOME PROBLEMS IN SUBGRADE MOISTURE CONTROL

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SYNOPSIS

The phenomenon of moisture accumulation and accompanying decrease in bearing capacity in soil subgrades beneath impervious pavements has long been recognized by highway engineers, but very little progress has been made toward quantitative analysis of the problem Rather, highway and airport engineers have leaned toward the assumption that all subgrades will eventually become saturated by capillarity and that pavements should be designed to withstand this extremely unfavorable subgrade condition

A recent survey of actual subgrade moisture conditions under both highway and airport pavements has revealed that some subgrades do approach saturation moisture content after a period of years of service, but that many subgrades do not approach this limiting condition. Rather, they seem to increase in moisture content subsequent to pavement construction and approach a fairly constant terminal value which may be appreciably less than saturation. Also the facts revealed in this survey are compatible in many respects with the implications of the Buckingham capillary potential concept, which has been utilized to a considerable extent by soil physicists in the field of agronomy, and the author is led to suggest that this concept of capillary flow and equilibrium may be a valuable tool for use in subgrade moisture studies and predictions

This paper gives a brief discussion of the Buckingham capillary potential hypothesis, of the relationship between capillary potential and various properties of soil, of the methods which have been developed to measure the relationship between capillary potential and soil moisture content and concludes with the suggestion that the terminal moisture content of a pavement subgrade may be predicted if the sorption characteristics of the soil and the distance to a free water table are determinable. The author also makes a plea for more complete long time measurements of subgrade moisture contents, soil temperature fluctuations, and capillary potentials under actual pavements in order to enhance our knowledge of this problem.

The very thorough compilation and digest of subgrade soil moisture data made by the Highway Research Board and reported by Mr Kersten (5)[1] a year ago provides highway and airport engineers with an excellent reservoir of factual information concerning this very important subject Among the many facts revealed by this study it is of particular interest to note the number of clay and silty clay subgrades in which the humidity of the soil, that is, the moisture content expressed as a percentage of the saturation value, was very high extending well up into the nineties in many instances Although Kersten's study does not deal with the condition or the probable life of the pavements resting upon these wet subgrades and does not offer a clue as to a limiting amount of moisture which can be

[1] Figures in parentheses refer to the list of references at the end of the paper

tolerated in a subgrade of a given type soil, a highway or airport engineer could rest much more easily if he knew with reasonable certainty in advance what moisture content to expect in the subgrade under his pavement. The tremendous influence of moisture content upon the bearing value of most subgrades is widely recognized, and while our present information in this field is largely qualitative, enough is known to emphasize the importance of maintaining a subgrade in the driest practicable condition.

A natural question which arises after study of this report on subgrade moisture conditions is "What can be done about it?" To what extent is it possible to predict the terminal moisture content of a subgrade which will be covered with a relatively impervious pavement? There is a tendency in current design procedures to assume that all subgrades, except those consisting of sandy coarse-grained soils will accumulate moisture and eventually become saturated under impervious pavements and that the pavement thickness should be sufficient to carry the traffic under such conditions. Kersten's data clearly indicates that some subgrades do approach saturation, but that there are also many which reach a terminal moisture content appreciably below this limit. Considerable value would accrue in the design of a highway or airport pavement and in the establishment of pavement grades if it were possible to make a reasonably accurate prediction of the moisture content of the subgrade during the service life of the pavement. This would reduce the necessity of applying the "side of safety" rule to all fine grained soil subgrades with resulting economy in many instances The purpose of this paper is to explore this question and to suggest in a preliminary manner some of the problems in the field of unsaturated soil moisture equilibrium and flow which need to be studied in order to approach an answer to the question.

CAPILLARY POTENTIAL

In 1941 the author in collaboration with Dr. M. B Russell (10) called the attention of highway engineers to the Buckingham capillary potential relationships in soil moisture, in the belief that this concept appeared to be a useful tool for attacking subgrade moisture problems. Many of Kersten's observations serve to strengthen this belief For example, he found that: (a) there was a tendency for subgrades which were relatively dry when the pavements were constructed to increase in moisture and to approach a fairly constant terminal moisture content which was considerably in excess of that existing at the time of construction; (b) several years were required for the subgrades to reach this terminal moisture content, (c) the moisture content of the subgrade soils increased with depth below the pavements; (d) the moisture contents were definitely a function of soil texture, being much greater in clays and silty clays than in the coarser textured soils; (e) there appeared to be a seasonal variation in moisture content, with a high point occurring in March and a low point in October, (f) the moisture contents were greater near the edges of pavements than under the central portions

All of the foregoing observed phenomena are in complete qualitative harmony with the capillary potential concept and strongly suggest that the subgrade soil moisture tended to reach a state of static equilibrium with the ground water tables below. An exception to the equilibrium situation appears to have existed near the edges of the pavements, where it seems probable that the equilibrium moisture contents were augmented by the soil drawing moisture laterally from successive waves of wetness as rain water falling on pervious shoulders penetrated downward toward the water table

The capillary or pressure potential idea was first advanced by Buckingham (2) in 1907. He reasoned that the flow of moisture through unsaturated soils was similar in many respects to the flow of electricity through a wire or the flow of heat through a rod or a wall: the flow in each case being from regions of high potential to regions of lower potential. In the case of moist soil and with the exceptions noted later, the attraction of the soil for additional moisture, whatever its cause, and the earth's gravitational pull provide the potentials which influence moisture movement, and wherever potentials are unbalanced, flow will take place Conversely, wherever potentials are balanced, the moisture seeks to attain a state of static equilibrium Ordinarily the pressure potential is less in dry soils than in wet ones, but this is not always true and moisture may flow from a relatively dry sandy soil into a wetter clay, if the characteristics of the two media are such that a potential gradient toward the wet soil exists. In other words, the criterion for unsaturated moisture flow from one soil region to another is the relative potential of the two regions and not their relative moisture contents. Also when capillary potentials are balanced with the gravitational potential the capillary soil moisture will approach a state of static equilibrium with a water table below and no upward or downward flow will take place. As a generalization with reference to texturally homogeneous soils, it may be said that with the moisture in equilibrium the soil will be saturated at the water table and will decrease in moisture content as the distance above the water table increases. It is this equilibrium phase of unsaturated soil moisture with which this paper is principally concerned.

A number of research workers in soil physics have expanded and amplified the original capillary potential concept as stated by Buckingham Notable among these are W. Gardner, L A Richards and M. B. Russell and the discussion of this characteristic of soils which follows has been taken largely from the works of these investigators.

Capillary potential in its simplest terms is a measure of the attraction of the soil at any given point for capillary water, or stated conversely, and more accurately, it is the work required to pull a unit mass of water away from a unit mass of soil For a given soil, the capillary potential is intimately dependent upon the moisture content of the soil. This is obvious since a relatively dry soil will exert a greater attraction for moisture than it will when wet, just as a dry blotter will soak up more water than a wet one Part of the attractive forces within the wet blotter have been satisfied by the previous moistening.

Other potentials exist in soil moisture in addition to capillary and gravitational potentials, as pointed out by Edlefsen and Anderson (3), such as that due to the adsorptive force field around the surface of soil particles and the osmotic potential which is due to dissolved material in the soil water. The first of these may assume paramount importance in relatively dry soils containing moisture in the neighborhood of and below the permanent wilting percentage, but subgrades at these moisture contents are not critical from the standpoint of subgrade bearing capacity. At higher moisture contents the influence of gravity far exceeds that due to the adsorptive force field, and it is believed that neglecting the adsorptive potential will not impair the applicability of the capillary potential concept to subgrade moisture problems. Likewise it is not considered that the osmotic potential will be important in subgrade moisture studies, although subsequent applied research may invalidate both these assumptions.

The most valuable discovery in connection with capillary potential and the one which has given the greatest impetus to its use in soil moisture studies is the fact that the capillary potential at any point in a soil mass is equal to the negative pressure or "tension" existing in the soil water at the point. This discovery, which is attributed to Gardner (4), has made it possible to determine quantitative values of the capillary potential since it is fairly easy and entirely practicable to measure the tension in soil water. The concept of tension in soil water may be illustrated by considering a vessel of water with a capillary tube extending upward from the water surface as shown in Figure 1. With water at equilibrium and if the free water surface is taken as the datum of zero pressure, it is apparent that the unit pressure at points below the water surface such as point B is equal to the weight of a column of water of unit cross section extending from the B level to the water surface In a similar manner, a tension exists at all points in the water in the capillary tube and the unit tension at any point C is equal to the weight of a unit column of water extending from C to the free water surface It will be observed that although the pressure at the free water surface is taken as zero, actually the pressure at this plane is atmospheric. Therefore values of tension up to one atmosphere are, in reality, positive pressures on the absolute scale. However, in applications of the capillary potential it is customary to consider the pressure at a free water surface as equal to zero and all absolute pressures less than one atmosphere are considered to be tensions.

The system shown in Figure 1 is analogous to a water system in a soil mass. The free water surface A may be likened to a water table in the soil, either actual or suspended, and the water in the capillary tube to the water in the capillary fringe above the water table.

From this analogy it is evident that when unsaturated soil water is in static equilibrium with a water table below and there is no tendency for the soil water to move upward or downward, the tension in the water at any point, and therefore, the capillary potential (since the two values are numerically the same though of opposite sign) is equal to a column of water of a height equal to the distance from the point to the water table.

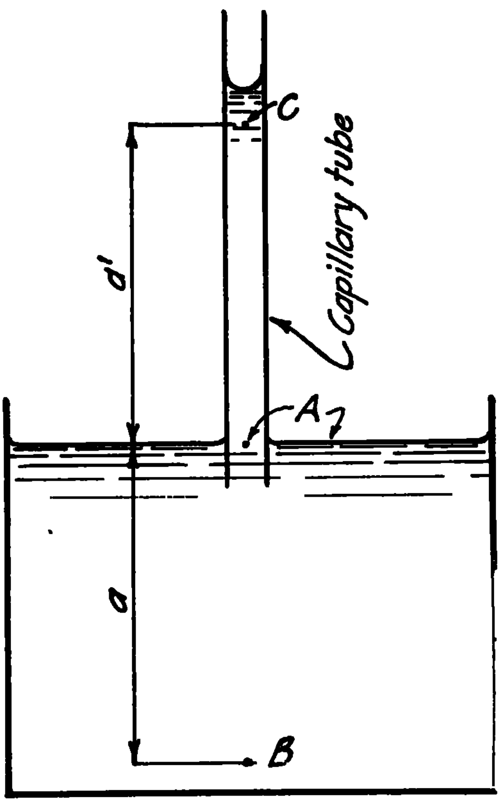


Figure 1. Pressure and Tension (negative pressure) in water

Corrollary to the foregoing discussion it is pointed out that the capillary potential of soil is always a negative quantity and can never be greater than zero. This characteristic results from the fact that capillary soil water can only exist under pressures less than atmospheric pressure When the pressure in soil water is atmospheric or greater, the water is free to move under the influence of gravity and cannot be characterized as capillary water.

Capillary potential will be spoken of in the algebraic sense, that is, the potential increases if it changes from -10 to -5 to 0 and vice versa. In this respect capillary potential is analogous to thermal potential when the temperatures involved are below zero Also it is pointed out that a low capillary potential is equal in magnitude but opposite in sign to a high tension in the soil moisture. This is readily visualized if it is recalled that the moisture in a drier soil is under relatively high tension, but moisture flow is toward the drier soil, other characteristics being the same, and therefore the potential is low.

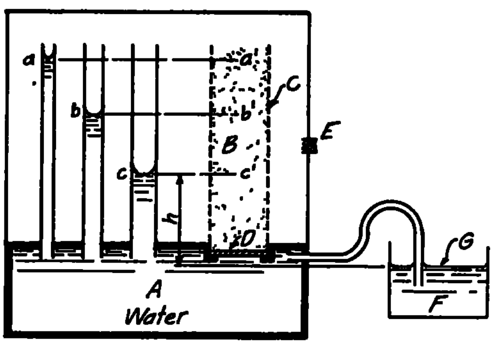


Figure 2. Capillary Tube and Soil Moisture Analogy (Richards)

THERMODYNAMIC RELATIONSHIPS IN SOIL WATER

As a closer analogy to the soil moisture situation and as a means of illustrating some of the thermodynamic relationships in unsaturated soil, consider the pressures and potentials in the system shown in Figure 2. Here a closed water tank A is fitted with capillary tubes having different diameters as indicated. B is a column of soil supported by a cylindrical sieve C and a porous clay plate D, which is readily permeable to water. The tubes and the soil column are inclosed in a case which is provided with a porous plug E to maintain atmospheric pressure within, but to prevent the loss of water vapor from the inclosure. When the tank A is filled with water and the auxilliary tank F is so adjusted that the free water surface is at G, water will rise in the capillary tubes and in the soil column and will reach an equilibrium distribution, provided the temperature everywhere in the system is maintained uniform. To simplify the analogy it is assumed that pure water and washed soil are used and that the water wets the capillary tubes and the soil particles to the same degree. When the system has come to equilibrium under isothermal conditions the water will have risen to various heights such as *a*, *b* and *c* in the capillary tubes in accordance with the well known formula $h = \frac{2T}{r\lambda g} \cos \alpha$ in which T is the surface tension of water, r is the radius of the capillary tube, g is the acceleration of gravity, α is the angle of contact between the capillary tube and the meniscus and λ is the density of water (λg is the unit of weight of water).

The configuration of the water as it exists in unsaturated soil is not definitely known, but it is probable that, except in very dry soil, it forms a continuous and connected configuration which spreads out in thin films over the surfaces of the soil grains and collects into various shaped wedges having definitely curved air-water interfaces where the grains are in contact or very close together. It is the relation between the potentials and forces in this water configuration which is of particular interest.

It is known that the vapor pressure of a liquid depends upon the curvature of the liquid surface. When equilibrium exists in the system of Figure 2, the surfaces of the water wedges in the soil at a′ must have the same curvature as the capillary meniscus at a, for if this were not true, there would be a difference in the vapor pressure at the two points. This would result in distillation and in motion of the water in a cycle which, according to the law of degradation of energy (the second law of thermodynamics) is impossible under isothermal conditions Thus it is seen that the pressure (negative pressure or tension) in the liquid at points of equal elevation above the free water surfaces, whether in the capillary tubes or in the soil, is the same

This discussion further substantiates the statement that, at equilibrium, the tension in capillary moisture at any point is equal to the height of a column of water from the point to a free water table. It follows, therefore, that if the relationship between the capillary potential of a subgrade soil and its various moisture contents were determined for appropriate temperature conditions, it would be possible to predict the terminal or equilibrium moisture content of the subgrade at various elevations above the water table. This proposition is based upon the assumption that the subgrade will be covered with a relatively impervious pavement and that the moisture in the subgrade will approach equilibrium with the water table as the source of moisture supply. Under normal circumstances where no pavement exists, moisture in field soils is seldom in a state of equilibrium. A portion of the rain falling on the surface percolates downward under the influence of gravity toward the water table, causing a wave of wetness between the surface and the water table. But before an equilibrium moisture distribution is established, evaporation may dry out the soil in the upper few inches near the surface to such an extent that the capillary potential in this region is greatly reduced. Under these conditions a potential gradient will develop in the upward direction from the wave of wetness and this moisture will be caused to reverse its direction of flow and rise in opposition to the gravitational pull. In this manner and due to other causes such as plant transpiration and soil temperature variations the moisture in the unsaturated soil above a water table is kept in motion by repeated rains and interspersed periods of evaporation. When an impervious pavement is built over a subgrade, rain is kept out of the soil and evaporation and transpiration are prevented. Also, the pavement may serve as an insulating layer which reduces the range and the rapidity of change of temperature fluctuations in the subgrade soil. These artificial conditions created in pavement construction are conducive to the establishment of equilibrium with the water table below and it seems probable that advantage can be taken of this situation in making predictions of the moisture content which will prevail in a subgrade after a pavement is built.

The application of this proposal will require knowledge of the elevation of the water table below a pavement and an estimate of the maximum elevation which the water table may attain during the life of the pavement. The water table or phreatic surface may be defined as the locus of points below the pavement at which the pressure in the soil water is atmospheric This corresponds to the height to which water stands in a test well, provided the water in the well and the water in the soil are in static equilibrium

Exceptions to the development of the equilibrium moisture distribution may occur near the edges of a pavement or in the vicinity of cracks or pervious areas in the pavement. Near the edge of a pavement in a humid climate, for example, a potential gradient toward the center region of the subgrade may develop as waves of wetness from successive rains falling on pervious shoulders travel downward toward the water table Such waves of wetness are zones of relatively high capillary potential so that water is forced or drawn into the relatively drier subgrade beneath the pavement. The fact of the existence of wetter subgrade soil near pavement edges has been noted by Kersten (5) and by Boyd (1) The reverse situation may develop in an arid climate, where long sustained evaporation from the shoulder surfaces may create regions of low capillary potential. Under these conditions moisture will flow outward from beneath the edges of the pavement, and the subgrade under the edges may become drier than that under the center.

As was seen in the consideration of Figure 2, the equilibrium value of the capillary potential in a soil column at a given height above a free water surface is a constant, independent of grain size, state of packing, temperature, angle of contact (degree of wetting) or dissolved material in the soil water. The percentage of moisture in the soil at this height, however, is dependent upon all of these factors It will be of interest to discuss the effect of these various properties of the soil and the soil water upon the relationship between capillary potential and moisture content. The difference between atmospheric pressure and the pressure in the soil water is dependent upon the surface tension and the radii of curvature of the surfaces of the little wedges of water which exist between the soil grains, in accordance with the formula $p = T\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$ in which p is the difference between the pressure outside and inside the meniscus, T is the surface tension and $\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$ is the total curvature[2] at a point on the meniscus. It would be possible to compute the capillary potential at any point in moist soil if the surface tension and radii of curvature of the water wedges could be measured. Obviously such measurements are impossible Nevertheless a consideration of these relationships serves to point out some qualitative effects of the soil and soil water characteristics upon capillary potential.

The surface tension of water is an inverse function of temperature. Hence a decrease in temperature increases the surface tension which decreases the pressure in the soil water and, therefore, the capillary potential. This means that cooling the soil increases its attraction for water, a fact which was demonstrated by Moore (6) who found that both the attraction for water and the rate of its movement were markedly increased in soil whose temperature was lowered. In all probability this fact accounts, in part at least, for the higher subgrade moistures in March than in October which Kersten (5) observed in the data which he collected from Illinois and Texas Myers (7) noted the same phenomenon in subgrade moisture studies conducted in Iowa.

An increase in the amount of dissolved salts in the soil water will increase its surface tension and thereby lower the capillary potential of the soil. It seems doubtful whether this effect would be significant in soil subgrades, except possibly in coastal areas or in regions of high soil alkaline content, but this cannot be stated as a fact and the matter needs to be investigated.

The other factors—moisture content, size of soil grains, angle of contact and state of packing—all affect the value of capillary potential through their influence on the radii of curvature of the water wedge surfaces As is indicated in Figure 3, A and B, if the amount of water collected between two soil grains is decreased, there will be an increase in the curvature of the air-water interfaces as the water recedes into the interstices and hence a decrease in the capillary potential. That is, the drier the soil, other factors being equal, the lower the capillary potential (greater tension) and the greater its attraction for moisture, a fact of common observation.

If equal weights of a fine and a coarse soil have the same moisture percentage, the fine soil will have more surface area and more points of proximity and contact between soil

[2] r_1 and r_2 are the radii of two curves formed by the intersection of two principal planes at right angles to each other and passing perpendicularly through the water surface at the point where it is desired that the curvature be known

particles. There will be less water collected at each of the contact points and the curvature of the surfaces will be greater as indicated in Figure 3, C and D. This results in a lower capillary potential in fine-grained soils and a greater attraction for moisture; also a fact of common observation.

The state of packing of the soil influences the capillary potential. In Figure 3, E and F, if two particles are pushed closer together the

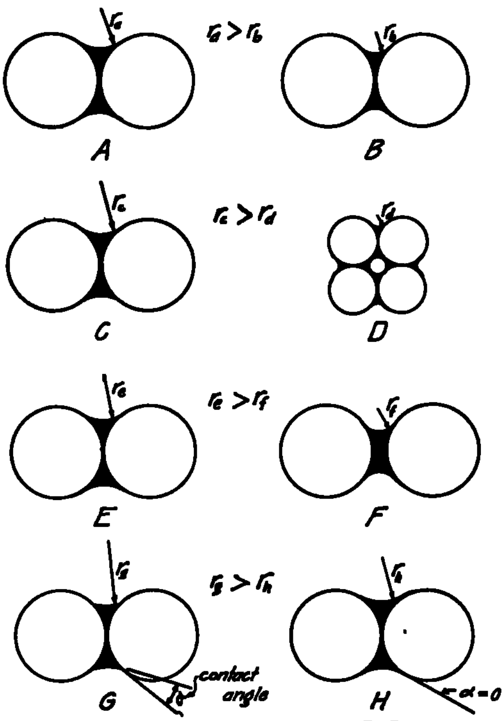


Figure 3. Soil Characteristics Influence Curvature of Air-Water Interfaces of Soil Moisture

curvature of the water surface will be decreased. If an isolated mass of relatively dry soil is sufficiently compressed, it will become saturated, that is, all the pores will become filled with water although the moisture content, expressed as a percentage of dry weight, will remain unchanged. During the process of compressing the soil the air-water interfaces gradually decrease in curvature and finally disappear and the capillary potential increases from a low negative value to zero. In the foregoing discussion an isolated mass of soil was considered to have been made more dense by compression or reduction in volume. If densification of the soil is obtained by increasing the amount of solid matter in a given volume, a very different result from that pictured will come about. In this case the number of points of contact between soil grains will be increased and the water wedges will be much smaller and have greater curvature, which tends to reduce the capillary potential of the soil in a manner somewhat similar to that discussed in the preceding paragraph. These facts are extremely important in connection with subgrade soil moisture studies and they dictate the necessity of measuring the capillary potential of such soils in their actual state of density and structural arrangement either in situ, or on undisturbed samples in the laboratory or on laboratory samples compacted to the density of the material in the finished subgrade, if quantitatively useful values of this potential are to be determined.

If the mineralogical composition of the soil is such that the soil grains are not completely wetted by water, the angle of contact between the water surface and the soil particles will be greater than zero which will tend to decrease the curvature of the water surfaces and thereby increase the capillary potential of the soil for a given water content. This is illustrated in Figure 3, G and H. Such a soil will have less attraction for water than one in which the particles are completely wetted.

SOIL SORPTION CURVES

Of all of the many factors which influence capillary potential, the moisture content of the soil is the most significant and useful. Curves showing the relationship between moisture content and capillary potential are known as "sorption curves" It has been demonstrated (10) that a sorption curve for a given soil, in a given state of packing and at constant temperature is a continuous curve from complete saturation to oven dryness Also it has been shown (9) that there is a decided hysteresis effect in the relationship between capillary potential and moisture content, depending upon whether the soil is wetting up or drying out This hysteresis is much more pronounced in fine grained soils than in coarser soils, and may amount to several feet of water tension in a very fine soil, the tension being greater (capillary potential less) for a given moisture content when the soil is drying out than when it is wetting up. The curve showing the relationship between moisture content and capillary potential when the soil is drying out is often called a "desorption curve" By the same logic, the sorption curve obtained when a soil is wetting up may be called an "absorption curve."

The reasons for this hysteresis phenomenon are not entirely understood but it seems probable it may be attributed to the fact that a suction is required to make air penetrate into a porous medium such as soil whereas water will penetrate more readily. During the process of draining soils, air enters and water is withdrawn first from the larger pores and then from successively smaller pores as drainage progresses. A higher tension is required to empty small pores and consequently at a given soil moisture tension, fine-textured soils will retain more water than coarser soils. Expressed in equivalent length of water column, the maximum tension that can be developed at any given point in field soil by downward drainage is equal to the elevation of the point above the water table It often happens that soils in the field have sufficiently small pores and therefore sufficiently high "air entry values" that they will remain saturated for appreciable distances above a falling water table This constitutes the zone of capillary saturation, which varies considerably in height with soil texture. On the other hand a rising water table would not be expected to saturate the soil above it to nearly as great an extent

Several typical sorption curves for soils of different textural characteristics are shown in Figure 4. Curves constructed from the same data but with the moisture contents expressed as a percentage of the saturation value are shown in Figure 5 The capillary potentials of these soils are expressed in negative feet of water and they are numerically equal to the tensions in the soil water. If long tubes were filled with these soils at the temperature and state of packing used in these determinations, and with their lower ends dipped into free water were allowed sufficient time to come to static equilibrium, then the distance above the water level would correspond numerically to the capillary potentials and the moisture percentages at any height for the different soils could be taken from the curves Stated in another way, if the soils used in these tests and the conditions under which the tests were conducted were representative of soils in actual subgrades, the equilibrium moisture content at any height above a free water table could be obtained from the curves as illustrated in Figure 6. The importance and usefulness of sorption curves in subgrade moisture studies is readily apparent. It is pointed out, however, that these particular tests were made on dry soil powder and their physical state and the temperatures prevailing during the tests probably did not correspond to the conditions which would prevail in an actual subgrade It is probable that sorption curves for subgrade soils in a reasonably dense state would begin at lower saturation values and that they would rise on steeper slopes in the regions of low tension. Also it is pointed out that an actual subgrade may consist of several strata of different soils between the base course and the water table. In such a case the sorption curve would be a composite curve of the various soils encountered.

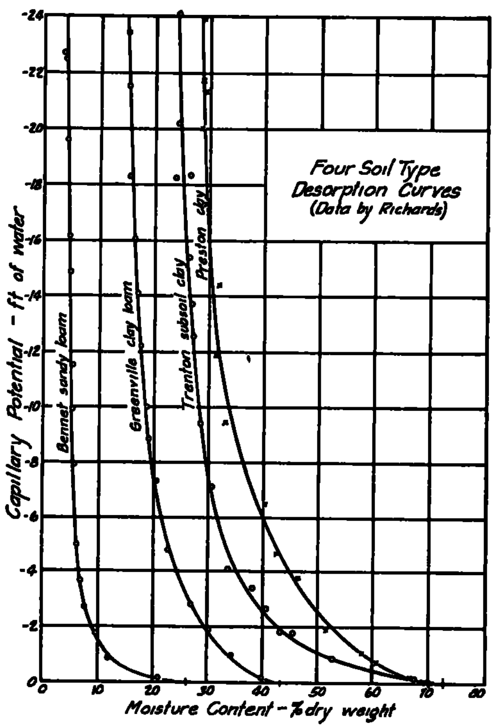


Figure 4

Attention is invited to the fact that the slope

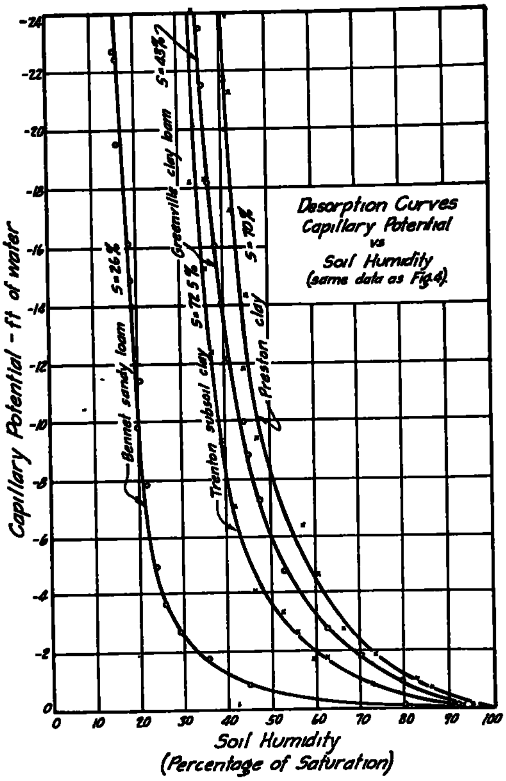


Figure 5

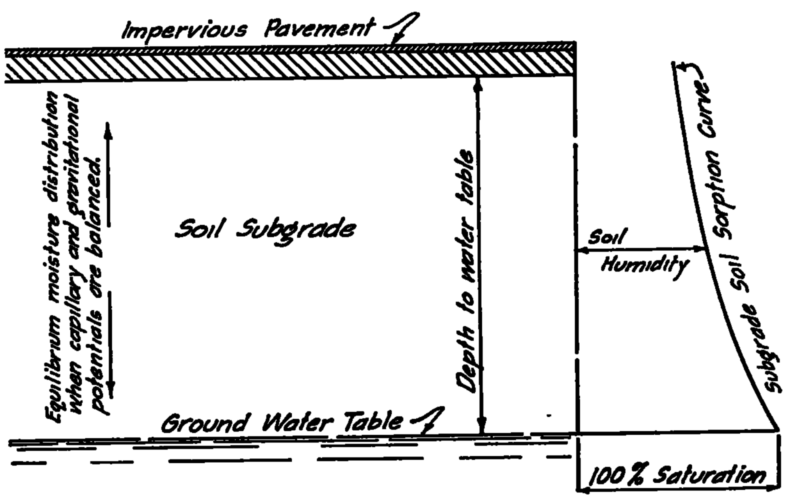
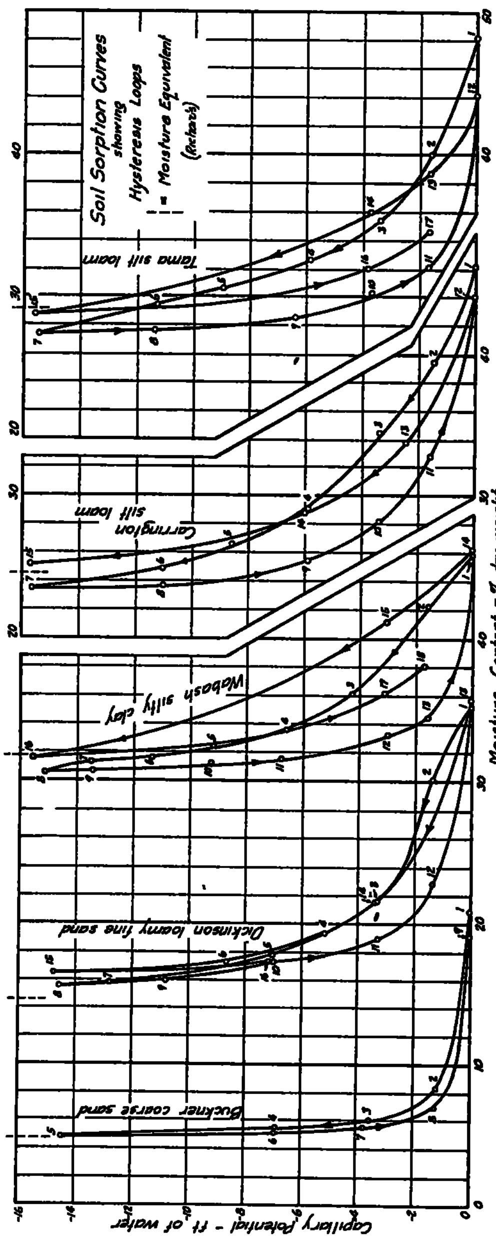


Figure 6. Subgrade Soil Moisture Distributions at Static Equilibrium with a Water Table

of these sorption curves is very steep in the regions of high moisture tension, which indicates a very gradual reduction in moisture content as the distance above a water table increases when the moisture is at equilibrium distribution. To the extent that these curves are typical of the relationships existing in actual subgrades, this would indicate that fairly high moisture contents may eventually develop in fine-grained subgrades beneath impervious pavements even though the distance to the water table is relatively great. In semi-arid regions where normal evaporation rates are high, the soil in its natural state may be very dry, but when it is covered with an impervious pavement, subgrade moisture contents may increase markedly as equilibrium develops, especially in fine-grained heavy textured soils. Kersten (5) noted that the subgrades in some projects included in his study showed moisture contents in excess of the plastic limit of the soils involved in areas where the annual precipitation was as low as 14 in., which seems to be compatible with the facts noted.

Another set of sorption curves is presented in Figure 7 to indicate the character of the hysteresis loops which develop when the soils are alternately drained and wetted between saturation and about the Centrifuge Moisture Equivalent. The numbers on these curves show the chronology of the points of observation at which the moisture content was allowed to reach equilibrium for various applied ten-



Soil Sorption Curves
showing
Hysteresis Loops
= Moisture Equivalent
(Richards)
Tama silt loam
Carrington silt loam
Wabash silty clay
Dickinson loamy fine sand
Buckner coarse sand
Moisture Content - % dry weight
Capillary Potential - ft. of water

Figure 7

sions. They show the characteristically wider hysteresis loops which develop in the case of fine-grained soils as compared to coarser soils. These curves give an indication of the hysteresis in moisture content when a water table rises and falls in a range of about 16 ft The loops would be correspondingly smaller for fluctuations of lesser amounts

In the discussion accompanying the curves of Figure 7, Richards (9) points out that considerable time was required for the attainment of moisture equilibrium after a change in the applied tensions, even though the maximum distance of travel for water in the samples used was only 3 in Equilibrium moisture adjustments corresponding to tension increases over a tension range from 0 to ½ atmosphere took place in 1 to 3 days, whereas tension decreases required 4 to 20 days Air dry loam soil in 6-in. irrigator pots required as long as 180 days to wet up to equilibrium with water supplied at a tension as low as 5 ft. of water. When considering moisture movements in unsaturated soils, and the time for the establishment of equilibrium, it appears to be necessary to distinguish between drying and wetting processes, the latter taking place at much slower rates under corresponding moisture conditions

Buckingham (2) also noted the long time required for moisture equilibrium to develop in his earliest experiments to determine the relationship between capillary potential and moisture content. In these experiments he placed soil in 2½-in. diameter metal cylinders which were about 40 in long and set them upright with their lower ends in water The tops of the cylinders were covered to prevent evaporation, though the covers were not air tight. After various periods the moisture distributions in the columns were determined. He found the distribution of moisture in Cecil clay to be widely different at the end of 66 days and at the end of 328 days and attributed the difference to the slowness with which moisture travels in this heavy soil. He was by no means certain that the equilibrium state of distribution had been reached even at 328 days, but did not carry the observations further.

The experiences of these investigators appear to be in harmony with the data collected by Kersten (5), which indicate that several years may be required for a subgrade under a pavement to reach a fairly constant terminal moisture content. Here again as in practically all matters involving moisture flow through soils, there was a wide difference in the characteristics exhibited by fine-grained and coarse soils

MEASUREMENT OF CAPILLARY POTENTIAL

Several methods of measuring the capillary potential of soils at various moisture contents have been developed, at least three of which appear to be practical in connection with subgrade soil studies. These three methods are centrifugation, measurement by means of tensiometers and by means of double-walled irrigator pots.

If a sample of soil is centrifuged at a constant angular velocity long enough to reach an equilibrium moisture content, it has been shown (10) that the capillary potential of the soil at that moisture content supplies the force which balances the centrifugal force acting on the soil water. Therefore, by testing the soil at several values of centrifugal force and determining the moisture content for each, several points on the desorption curve for that soil could be determined and the curve constructed In the standard AASHO and ASTM tests for Centrifuge Moisture Equivalent, the sample is centrifuged at 1000 times gravity which gives a value of capillary potential equal to minus 16 4 ft. of water Therefore C M.E represents the moisture content which the soil would contain if it were in equilibrium with a water table approximately 16 ft. below. However, the sample in the centrifuge is not in the same physical state as the soil in the subgrade, particularly with respect to the size and arrangement of its particles and to its state of packing or density Therefore, the C.M.E. as now standardized must be considered as a qualitative value and the standard centrifugation process would need to be modified to obtain quantitative values for use in making subgrade soil moisture analyses. Furthermore, during centrifugation the soil sample is subjected to a compressive force which might make it difficult to maintain a state of packing during the test comparable with that of the subgrade soil. This discussion is not intended to rule out the centrifuge method as a possible means of obtaining desorption curves for subgrade soils, but is merely for the purpose of pointing out some of the difficulties involved

An apparatus for measuring capillary potential known as a "capillary potentiometer" or more simply a "tensiometer" has been developed, the essential features of which are shown in Figure 8. It consists of a porous cup, A, sealed onto a glass tube which is connected by heavy pressure tubing to a mercury manometer, B. The porous cup and the manometer are filled with water, a rubber stopper inserted at C, and the cup is imbedded in the soil, making sure of intimate contact between cup and soil When water moves from the cup into the soil, the tension within the cup is increased and the mercury rises in the manometer This process continues until the soil water and the cup water have the same tension The difference between this tension and the pressure of the atmosphere is numerically equal to the capillary potential of the soil and may be determined directly by reading the manometer Instruments based upon this same principle have been developed for measuring the capillary potential of soils in situ and are described in reference (10)

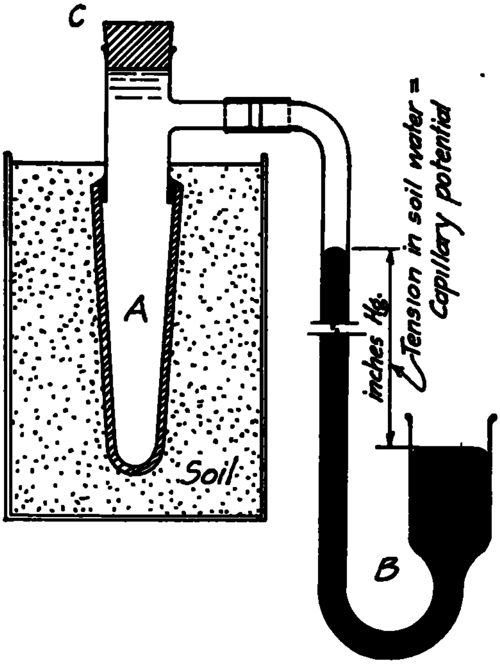


Figure 8. Soil Tensiometer (Richards)

Tensiometers appear to have considerable value for laboratory determinations of the capillary potential of subgrade soils as well as for long time continuous observations of this potential in the field. In the laboratory the soil should be compacted to the state of density which will exist under the pavement and sorption curves obtained for the appropriate temperatures which will prevail under the completed structure.

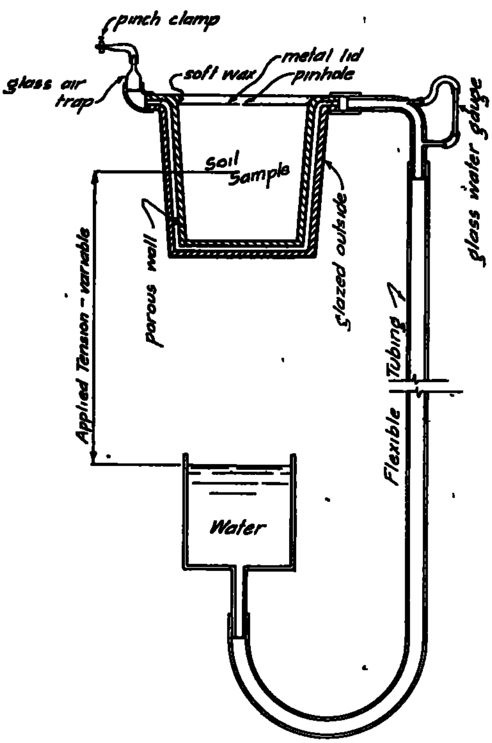


Figure 9. Double-walled Irrigator Pot (Richards)

The third method of measurement, which is believed to have distinctly favorable possibilities for successful use in subgrade soil moisture studies, is by means of double-walled irrigator pots. Pots of this kind were used by Richards in the determination of the sorption curves shown in Figure 7 and they are illustrated in Figure 9 They are constructed in one piece having a glazed outer wall ¼ in. thick, an unglazed inner wall ¼ in thick and an inter-wall space of ¼ in for the supply water. The soil cavity is 6 in in diameter at the top and 5 in at the bottom and 6¾ in. deep. An air trap is provided for the removal of accumulated air at the pot. The inter-wall space is connected at the top to long flexible tubing which terminates in an open reservoir which is adjustable for height in relation to the soil sample in the pot. The distance from the center of the sample down to the water level in the reservoir represents the applied tension in the soil water and may be measured with a steel tape or by other suitable means.

Knowing the weight of dry soil, the tare weight of the pot, and the moisture content of the soil corresponding to the gross weight of the pot at any one time, the average moisture content of the soil at any other gross weight can be calculated. After the soil sample is placed in the pot, a thin sheet metal lid may be sealed in place with soft wax to prevent evaporation, but a small pin hole should be left in the lid so that the soil air will remain at atmospheric pressure. In the experiments reported by Richards (9), the pots were disconnected from the supply tubing by a suitable arrangement of pinch clamps whenever observations of water content of the soil samples were made. This procedure could be eliminated by setting the pots on small platform scales so that weights could be determined at any time without moving the pots.

CONCLUSIONS

On the basis of the facts discussed it is believed that the Buckingham capillary potential concept holds considerable promise for practial application to subgrade moisture problems, particularly those which involve moisture equilibrium in the capillary fringe Some modifications and adaptations of sampling and testing methods now in use by soil physicists working in the field of agronomy will need to be made to make the concept usable in connection with pavement subgrades, but none of these appears to be particularly difficult. It is believed that this subject merits the attention of research workers and of engineers engaged in the design and construction of highway and airport pavements, particularly those of the flexible type

Supplementary to the studies which will be necessary to make practical applications of this concept, there is need for a great deal more detailed information concerning actual subgrade moisture conditions and fluctuations. Kersten's study (5) is a splendid beginning, but it lacks detail and complete information. This is because it was made from data taken independently by a large number of agencies without coordination of purpose and methods. A great deal of value would accrue to state highway departments and airport officials if long time studies of moisture conditions, temperature fluctuations, ground water table fluctuations and capillary potentials of subgrade soils were made at permanent observation stations widely dispersed throughout the areas under their jurisdiction To facilitate the procurement of data of this kind, automatic instruments for recording temperatures, moisture contents and capillary potentials at various depths in the soil need to be developed. Everyone is now familiar with automatic traffic recorders, and automatic stage registers are in widespread use in studies of stream flow and water resources. This same idea of continuous long time recording needs to be applied to the collection of information concerning the subgrade moisture problem.

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DISCUSSION

CHAIRMAN HOGENTOGLER: I would like to ask just one question of either Professor Spangler or Doctor Winterkorn As water changes from bulk phase into film phase, does surface tension change?

DR. WINTERKORN: Yes, indeed Surface tension is one of the outward evidences of the forces with which water molecules attract each other. A molecule in the interior of the liquid mass is attracted uniformly by all surrounding molecules; one on the surface is subject to a one-sided pressure which tends to take it out of the surface and thus to decrease the total surface area This phenomenon integrated over all the molecules located in the surface results in the so-called surface tension

It is thus evident that surface tension increases with increasing intermolecular attraction in a liquid i.e. with increasing internal pressure. If the density of a structureless liquid is an indication of the effective internal pressure, then the surface tension should rise with increasing density. This is true for water at temperatures above the range in which structural disturbances occur.

The effective internal pressure in an aqueous system is increased by strong electrostatic attraction originating on surfaces of soil particles and on dissolved ions As the internal pressure is increased, so is the density and the surface tension of the aqueous phase. It appears that the increase in surface tension of water is about 6 dyne per 1 per cent increase in density.

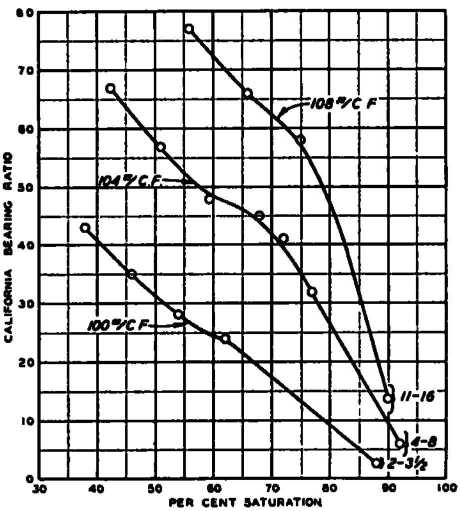
The increased density of water resulting from adsorption forces entails an increased internal friction. This is obvious, since the viscosity of a liquid depends on the number of intermolecular spaces available into which the liquid molecules might move, thus making flow possible. The energy required for making such holes and, consequently, the viscosity of the liquid increases with increasing internal pressure and, therefore, also with decreasing distance from the adsorption surface.

I might conclude by saying that soil-water relationships such as swelling, hygroscopicity, heat of wetting etc. are only outward manifestations of the relative affinity of water molecules for each other and for the soil constituents respectively.

MR. W. K. BOYD, *U. S. Waterways Experiment Station:* Mr. Spangler has again called attention to the existence of a possible laboratory tool available to those engineers concerned with the design of highway and airfield pavement facilities. The hypothesis developed in his paper is basic and serves as a solid foundation upon which a practical approach may be subsequently developed that probably will give specific values for assistance in determining actual pavement thickness requirements A technical discussion in regard to the theoretical aspects of the problem is not contemplated by this discusser. This can well be delayed until interested research agencies have had the opportunity to delve more deeply into the study. Rather, this discussion will be devoted principally to a demonstration showing the effects of moisture in a subgrade on its bearing capacity and will outline briefly some of the factors that must be considered.

The U. S. Corps of Engineers has long been keenly interested in and aware of the economies possible in pavement design if some soil moisture percentage less than complete saturation could be reasonably anticipated. An expression of this interest is the fact that an investigation is now in progress at three airfields in the Albuquerque, New Mexico, Engineer District to determine the moisture content variations that may occur in the subgrade beneath pavements in arid regions over a long period of time. This study is being conducted jointly by the Albuquerque District and the U. S. Waterways Experiment Station at Vicksburg, Mississippi. It is expected that the latter office will consider carefully the excellent ideas expressed in Mr. Spangler's paper to further their studies in this field.

It is not possible at this time to present with complete accuracy the effect of moisture on the bearing capacity of subgrade materials. Engineers who have studied the behavior of soils under stress recognize that many factors are involved even under closely controlled laboratory conditions Eustis and McRae[1] have directed attention to the fact that the stress-strain characteristics of remolded and compacted soils vary considerably with variation in molding water content, density, and method of compaction. These differences in physical behavior occur in some materials even though they are brought to the same density and degree of saturation before testing by several types of shear test For the reasons discussed by Eustis and McRae the data presented here should be considered as approximations to provide qualitative rather than quantitative comparisons



PER CENT SATURATION	C BR	REQUIRED BASE PAVEMENT THICKNESS-INCHES 5 000 LB WHEEL LOAD	37 000 LB WHEEL LOAD
	DENSITY 100 LBS/CU FT		
70	17	6*	12
80	9	8	19
90	3	14	37
	DENSITY 104 LBS/CU FT		
70	42	6*	9*
80	26	6*	9*
90	9	8	19
	DENSITY 108 LBS/CU FT		
70	62	6*	9*
80	48	6*	9*
90	14	6	14

* MINIMUM REQUIREMENT BASED ON CONSIDERATIONS OTHER THAN SUB-GRADE BEARING

Fig. A. California Bearing Ratio vs. per cent Saturation—Vicksburg Loess

On Figure A curves are presented that compare the bearing capacity of a silty soil (measured by the California Bearing Ratio method of test) with water content (per cent saturation). The data from which these curves were prepared have been taken from plates 84 and 86 of a report entitled, "The California Bearing Ratio Test as Applied to the Design of Flexible Pavements for Airports," prepared by the Waterways Experiment Station These curves show the variation of California Bearing Ratio (CBR) with per cent saturation based on the result of tests on laboratory compacted samples of a silt soil. Three curves are shown each representing a definite density, namely, 100, 104, and 108 lb per cu ft. The data from which these curves were developed were obtained from samples compacted at molding water contents ranging from 10 to 18 per cent and for three compactive efforts CBR tests were conducted on the samples immediately after compaction or in the "as-molded" condition. It is noted that in all cases the CBR decreases rapidly with an increase in per cent saturation. In addition to the tests in the "as-molded" condition, tests were conducted on "soaked" samples. In these tests, samples were compacted at the same molding water contents and density as for the "as-molded" tests but were immersed in water for 4 days prior to testing for CBR. The samples were confined with a 10-lb surcharge during soaking The

[1] "Stress-Strain Characteristics of Compacted Soil Systems," by Joseph B Eustis, Asst. Chief of Embankment & Foundation Branch, U. S. Waterways Experiment Station, and John L. McRae, formerly Asst Engr, U S Waterways Experiment Station, now with U. S Navy. Presented at Annual Meeting, American Society of Civil Engineers, New York, N. Y., 19 January 1945

results of these tests are shown numerically alongside each curve The values for any one density show the range of CBR obtained for tests conducted on samples that were compacted at varying moisture contents.

On the right hand side of Figure A are tabulated the CBR values for 70, 80, and 90 per cent saturation for this particular soil compacted to densities of 100, 104, and 108 lb per cu ft. The value of 90 per cent represents practically saturated conditions. The CBR values were read from the curves on the left hand side of Figure A Also shown in the table are the thicknesses of base and pavement that would be required for wheel loads of 5,000 and 37,000 lb. The thicknesses were taken from the design curves presented in Chapter XX of the Engineering Manual prepared by the War Department, Office, Chief of Engineers. Assuming that the soil is compacted and maintained at a density of 100 lb per cu ft, the pavement thickness requirements for a 5,000-lb wheel load range from 6 in at 70 per cent saturation to 14 in. at 90 per cent saturation The 6-in. thickness is a minimum requirement that has been established for reasons other than to protect the subgrade The actual minimum requirements for 70 per cent saturation from the standpoint of subgrade strength would be 5 in For a 37,000-lb wheel load, the corresponding variation is from 12 to 37 in. Similar savings in thickness requirements are noted when the soil is compacted to 104 or 108 lb per cu ft. Thus it can be seen that appreciable savings can be accomplished if it can be assumed that the soil can be maintained at a water content less than complete saturation. It is also apparent that the density to which a soil is compacted is as much a factor as the per cent saturation. The thickness requirements for a 37,000-lb wheel load for the soil at 90 per cent saturation would be 37 in. if the soil is compacted to 100 lb per cu ft but would be only 14 in if compacted to 108 lb per cu ft.

As Mr Spangler has pointed out, experience indicates that highways as now constructed permit the shoulders to become fully saturated during certain periods of the year while beneath the center of the pavement the subgrade may have a much lower moisture content. Before the highway engineer can take advantage of Mr. Spangler's hypothesis in conjunction with the reduction in pavement thickness just illustrated, he must be prepared to consider one of two alternatives: (1) increased thickness of pavement at the shoulder, or (2) protection of the inslope from surface water. Some highway departments now recognize the probable loss in subgrade bearing at the shoulders and provide for a thickened edge design for their flexible pavements. Consideration has been given by some highway departments to the placement of an impervious blanket on the inslopes to protect against the entrance of water from the side ditches In the case of airfield design with runways constructed that have impervious surfaces 100 to 300 ft wide, the possible savings in pavement thickness requirements are material and are not affected by the shoulder conditions to the extent previously cited However, both highway and airfield engineers must consider that their pavement facility remains in position over a long period of years and will be subjected to the destructive forces of nature and traffic which may permit the entrance of surface water at some future time. They must consider frost action and the possibility of a fluctuating water table as they influence subgrade moisture content. They must further consider the variations in soil types possible in small localized areas which may become saturated to an amount higher than the average. An airfield located in an arid region was found to have moisture contents in the subgrade that varied between 40 and 90 per cent of saturation with a low average of about 50 per cent and a high average of about 80 per cent A conservative design would necessarily be based on the latter figure Considering the number of factors and variables that are involved, some of which have just been discussed, it is obvious that only broad generalizations can be made by the design engineer

Three methods are discussed in Mr. Spangler's paper whereby the capillary potential of soil can be determined for various conditions of moisture and density. It is to be hoped that the method selected as a laboratory test will involve procedures that are simple and can be performed quickly. In this respect, it is suggested that the centrifuge moisture test or a modification thereof be given careful consideration. It is admitted that the test has shortcomings as pointed out by Mr. Spangler. However, it is now a recognized routine A.A.S.H.O. test performed by many soils laboratories. It is entirely possible that the value known as the centrifuge moisture equivalent can be used to develop qualitative relationships between different types of soils and the probable degree of saturation that can be expected for each for any given group of conditions. While this method would involve incorporating empirical considerations into an otherwise rational approach, it should be remembered that practically all other factors involved in pavement design have as their basis empirical data

Mr. Spangler mentions the fact that in the centrifuge process the sample is subjected to a compacting force that is considerable. It is possible that this difficulty can be alleviated by using a suction method to remove the water from the sample rapidly. A suction-moisture content equivalent has been developed and is used by some soil laboratories as a substitute for the centrifuge moisture equivalent

PROGRESS REPORT OF SPECIAL PROJECT ON STRUCTURAL DESIGN OF NONRIGID PAVEMENTS

SUBGRADE MOISTURE CONDITIONS BENEATH AIRPORT PAVEMENTS

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University of Minnesota

SYNOPSIS

The report presents an analysis of subgrade moisture data obtained from airfield evaluation reports of the Office of Chief of Engineers, War Department; the moisture contents beneath both rigid and flexible airport pavements in 8 Disdricts, extending from the southeastern humid area of the country to the arid southwestern section were studied. It was found convenient to divide the soils into textural classes and to express the moisture contents in terms of percentage of saturation, percentage of plastic limit, and percentage of optimum moisture content

The moisture conditions, expressed in all three ways, varied with the texture of the soil and the climate of the region. The average condition increased for a textural progression from sands through sandy loams, clay loams, and clays The percentage of the soils which were 90 per cent or more saturated or were wetter than their plastic limit or optimum moisture content was higher for the heavier textured soils than for the light ones In humid or semi-humid areas, the sands and loamy sands had low relative saturation values, the sandy loams were variable, and the heavier soils showed up to more than half their values in excess of 90 per cent saturation A majority of the soils other than sands were wetter than their optimum moisture content

The data obtained from arid or semi-arid regions showed the subgrade conditions in such areas to be definitely drier than those in humid regions. Even the heavier textured soils tended to exist at relatively low moisture contents.

Comparisons of the moisture contents in similar soils beneath rigid and flexible pavements on the same airfield generally showed the greater values for the rigid type.

In arid regions the variations of moisture content in the upper 3 ft. of subgrade were slight and showed no definite trends

The report "Survey of Subgrade Moisture Conditions"[1] presented the results of a study of moisture conditions under highway pavements. This paper is an extension of that study and is concerned with the conditions under airport runways, taxiways, and aprons. The data were obtained from the airfield evaluation reports of the U. S. Engineer Department

The airfield pavement evaluation program was initiated by the Office of the Chief of Engineers late in 1943 and continued through the following year. Its prime purpose was to determine the weight of planes that could safely use each field without overstressing the pavements. Included in the program were

[1] *Proceedings*, Highway Research Board, Vol 24, p. 497, 1944