REPORT ON SUBGRADE INVESTIGATIONS FOR THE YEAR 1925

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During this year investigations and studies have been made on several phases of the subgrade problem in the field and at the Arlington Experiment Station Considerable work has been done on the relations between subgrade soils and water

SUBGRADE SOILS

Ideal soils for subgrades are those which have a high content of relatively coarse crystalline material with sufficient fine material to bind the larger particles together This fine material should not have high plasticity or high volume change, which would hinder perfect drainage of the soil structure Subgrade soils which are mottled, gray or blue in color may be regarded as having poor drainage, even though the topography is ideal for good drainage

Certain soils in every State in the union have structures which are open, crumbly, and have profiles which guarantee good drainage, while others are plastic, sticky or compact, and have poor internal drainage. One stratum of a soil may have a texture which would drain readily but is underlaid by another stratum so dense and impervious that it cannot be penetrated by water except in the capillary form.

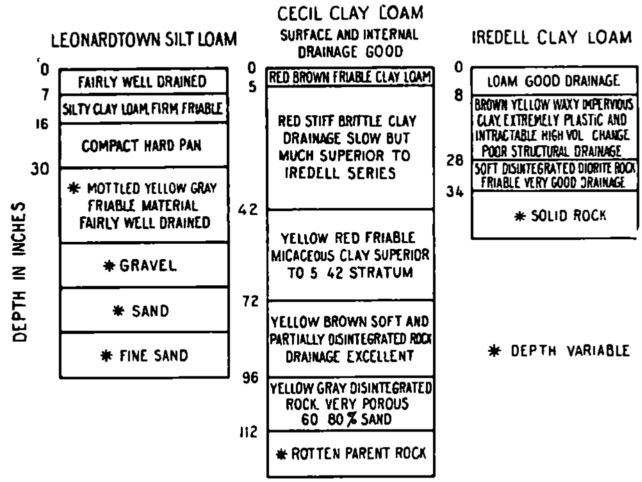


Figure 1—Profiles of Leonardtown, Cecil, and Iredell Soils

Figure 1 illustrates the profile of such a soil, and it has been given a specific name When this soil is definitely described and its name given, its identity becomes as definitely fixed as that of a plant or animal. Soil families or series have their ranges of color, structure, etc, within certain limits just as animate or inanimate objects When once seen, the name Iredell soil carries with it a picture of difficult drainage and high volume change, the Cecil series is associated with friability, easy drainage, etc, while the Leonardtown has a compact layer which obstructs free structural drainage

Some soils which have been weathered for long ages have very compact subsoils which are almost impervious to percolating water. Such subsoils originate from the infiltration of water laden with soil suspensions from above and when such soils are located beneath pavements, drainage will be imperfect

In certain soils which have been deposited in water will be found lenses of extremely fine textured clay and silt, which must be considered in the design of roads Strictly speaking, uniform soils are rarely encountered and for this reason intimate knowledge must be obtained of the changes in soil structure and an adequate drainage system fitted to the needs of each individual condition, or vast differences in moisture conditions in the subgrade soil will develop during seasons of high precipitation All highway engineers recognize the absolute necessity of studying the topography and planning for adequate surface drainage, but almost no attention is given to subsurface drainage unless free water is encountered at the time of construction

THE MOVEMENT OF SURFACE WATER

Water of this class which reaches the roadway comes from direct precipitation or flows from some contiguous slope from which the roadway has not been adequately protected While all road builders realize that surface drainage is of paramount importance, yet an inspection of our most modern roads will almost invariably disclose many instances of gross neglect in adequate surface drainage Water reaching the subgrade in this manner was identified last winter in the vicinity of Wilmington, North Carolina

Following a rain which fell on February 8, the edges of concrete pavements were observed to be covered with moisture which extended to the lower surface of the pavement to the extent that considerable moisture had overspread the subgrade as far toward the center as could conveniently be determined Although careful examinations for moisture in the subgrade had been made many times daily prior to the 8th, no such condition had been found to exist On road sections where a good grade of top soil had been used for forming the shoulders, this wet condition on the edges of the pavements or in the subgrade was not found The reason for this is attributed to the low shrinkage of this type of soil, which does not form a joint of any considerable opening at the plane where the shoulder and pavement meet, thus preventing the ingress of moisture in harmful quantity

When water begins to flow into this joint, it is soon filled with sand and clay particles to such an extent that the joint is sealed so as to prevent further ingress of water It is believed that this condition in sand-clay soils has been noted a sufficient number of times during this and other investigations to state this as an established fact

Too many cuts are left unprotected from hillside slopes and become soaked from water which should never be permitted to drain in that direction In flat and gently rolling sections too often the shallow side drains are clogged with hardened or slowly melting snow and the subgrade becomes unstable, especially under heavy loads Too much emphasis cannot be given to keeping side drains and outlets open under these conditions, because it is under such conditions that roads suffer most

THE MOVEMENT OF GROUND WATER

For convenience in discussion, ground waters will be divided according to form into three classes

Gravitational water
Capillary water
Vaporized water

Gravitational Water—As soon as water is precipitated upon the ground it begins to penetrate the soil through areas of least resistance The greater portion of the water entering the soil is dependent upon the force of gravity for its major movements. Water collecting in little pools or depressions on the surface creates low heads which assist in forcing the water into soil pores, joints, and cracks

In residual soils the joints, bedding planes and fissures in the original rock structure continue to carry free water long after the rock has weathered into clay These joints may be traced in almost any fresh cut and percolating water may be found in them after rains

On drying, soils having high coefficients of shrinkage produce shrinkage cracks, in some cases to considerable depth Such cracks, while apparently closed by a subsequent increase in soil volume, are not destroyed but continue to function in proportion to the size of the opening Cracks are also produced by frost action, earthquake tremors, unequal pressures, and perhaps many other causes, but the important consideration is their universal presence in all parts of the earth's surface

During periods of considerable rainfall water may be seen spouting from the face of cuts in many localities, although frequently the flow is only sufficient to produce a wet spot which is spread by capillary tension Such a condition as this is possible, as shown on the left face

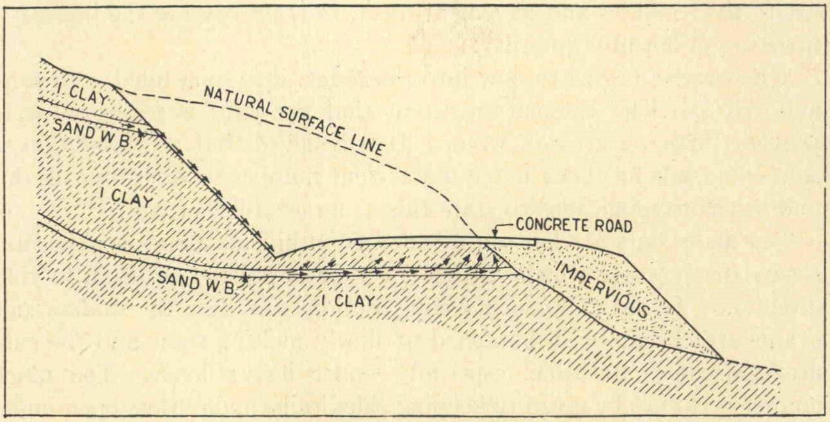


Figure 2—Gravitational Water in Cuts

Figure 3—Wet Cut with Pavement Failures

of the cut in Figure 2. In Figure 3 the dark area on the face of the cut at the extreme right indicates a saturated condition of the soil, and the cracked area in the left center of the pavement bears mute evidence of insufficient support to the pavement. Several borings into the subgrade furnished unmistakable evidence of seepage water in harmful quantity.

Figure 4 shows a coastal plain soil profile which is conducive to producing wet cuts. The dark sections on the face of the cut were supersaturated with water, which was spouting out when the photograph was made. A similar condition existed at a level below the pavement, but a sand and gravel layer beneath the pavement and intercepting

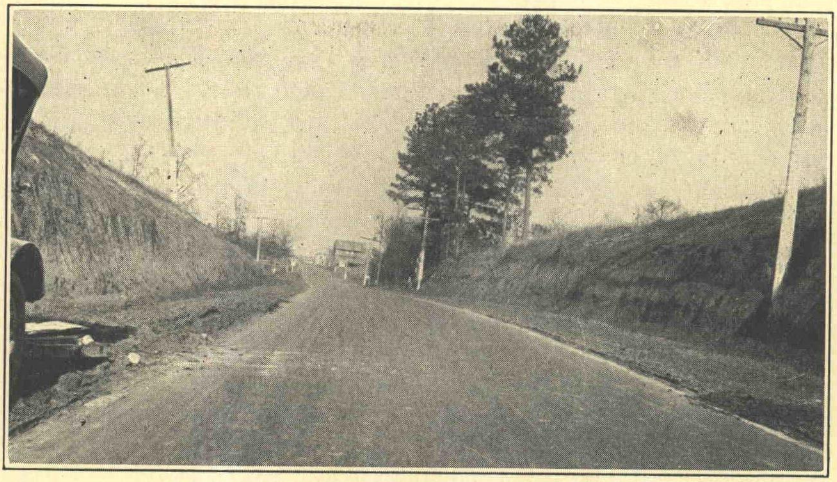


Figure 4—Saturated Strata in a Costal Plain Cut. Subgrade treated and drained. No Pavement Failure

lateral drains prevented this seasonal seepage water from producing a subgrade failure.

In every section visited there have been found strata of material which was the source of water in cuts at some period during the year.

The character and general appearance of aquifers described in the foregoing paragraphs indicate that they are seasonal and are active only after periods of considerable precipitation. No attempt has been made to record all observed harmful conditions of this kind, but to describe characteristic types and call attention to the effect on pavement conditions.

The activity of a water-bearing stratum under a pavement for a period of one week may be sufficient to cause serious damage to an expensive pavement.

Capillary Water.—The distinction between capillary and gravitational water is not definitely defined. Particles of water of such size as will move between soil particles under the force of gravity may be held or moved against the force of gravity when the temperature of the soil is decreased so as to produce a surface tension in the soil particles greater than the force of gravity. These same water particles will again be transferred from the control of surface tension to gravity upon the soil becoming warm enough to decrease its capillary force to less than the force of gravity.

The laws governing the movement of capillary moisture are not well understood, and there are various and conflicting opinions as to the effect of this form of water in soils. In our investigations this form of soil moisture has received considerable attention in the field as well as in the laboratory. The value of increasing the height of an earth fill above the water table on lowering the percentage of capillary moisture held in the soil at the top should be determined This involves two problems—one in capillarity, the other in evaporation To differentiate between water moving under capillary tension and water moving in the vaporized form has not been an easy problem

Highway engineers have in many cases determined suitable heights above water tables which produce reasonably dry subgrades This distance varies with clay types and their environments There are types of clay subgrades, however, which have such a high capillary potential that the moisture held in the soil at a considerable height above the water table is sufficient to reduce the bearing value to a point where the subgrades will not give adequate support to pavements

Numerous tests for discovering the causes which affect or determine the capillary potential of soils have been made by various investigators in soil physics and the following laws are well established

1 The height to which capillary moisture will rise in soil is in inverse proportion to the size of the soil pores In glass tubes water will be lifted ten times higher in a 0 01-inch tube than in a 0 1-inch tube
2 The percentage of capillary moisture held in a uniformly graded and compacted soil column free from evaporation decreases as the height above the water table is increased
3 The percentage of mositure held under capillary tension diminishes as the temperature increases
4 The known factors governing the capillary potential are size of pores, chemical and physical character of soil particles, their temperature, barometric pressure, and the degree of humidity of the outside air

In North Carolina observations were made to determine what seemed to be the necessary depth of lateral drains which insure proper drainage of the subgrade These observations were made on all the soil types crossed between the mountains and the sea Many borings and excavations were made under pavenemts for examining the wetness of the soil at points where failures were found as well as points where no failure existed.

No failure was found where the subgrade was as much as 12 inches above the water surface in lateral drains, even in the heavier clays encountered In passing from the heavier clays to the loams, this distance between the subgrade and water surface in the side drains could be safely decreased, as was shown by the reduced moisture content in the sandy subgrades as compared with the clay subgrades This statement applies to conditions of drainage where no aquifers of any type were evidenced.

It should be stated that it is not intended to convey the impression that 12 inches is suggested as being a sufficient height for the subgrade to be placed above the water-table under any condition other than those observed There are soil and climatic conditions where a distance of several feet between the water-table and subgrade will not guarantee good support without special design of subgrade or pavement

At the time the field work was being done for this study, it was believed possible to get a relation between the capillary moisture as found in the field and the capillary moisture as determined in the laboratory, but from the field data obtained the determination of this relation has not been possible It is a well-known fact that, in a general way, the percentage of capillary moisture decreases with the increase of height above the water-table, but the laws which govern this are not well known

The laboratory method used for studying the capillary potential of soils is one described by C J Lynde and H A. Dupre, Macdonald College, P Q , Canada, in the Journal of American Agronomy, Vols 5 and 6, 1913–14 A view of this apparatus is shown in Figure 5 Briefly, all air particles are first driven out of the soil by boiling in water The water and soil are then placed in a 40 mm filter-plugged funnel and centrifuged for compacting the soil and draining out a part of the soil water It is essential that some free water be held on the surface of the soil and that the stem of the funnel remain filled with water. At the conclusion of the filling and centrifuging process the funnel is connected with a ½ mm capillary tube previously filled with boiled water, the connecting joint between the funnel and capillary tube made

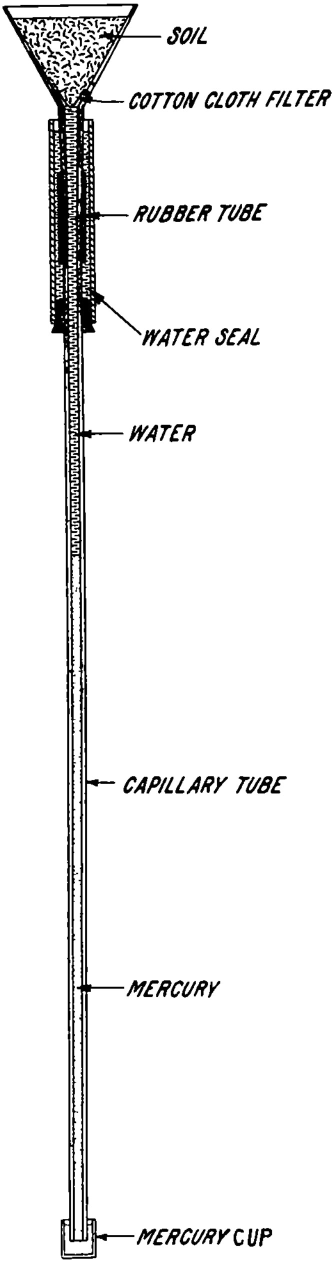
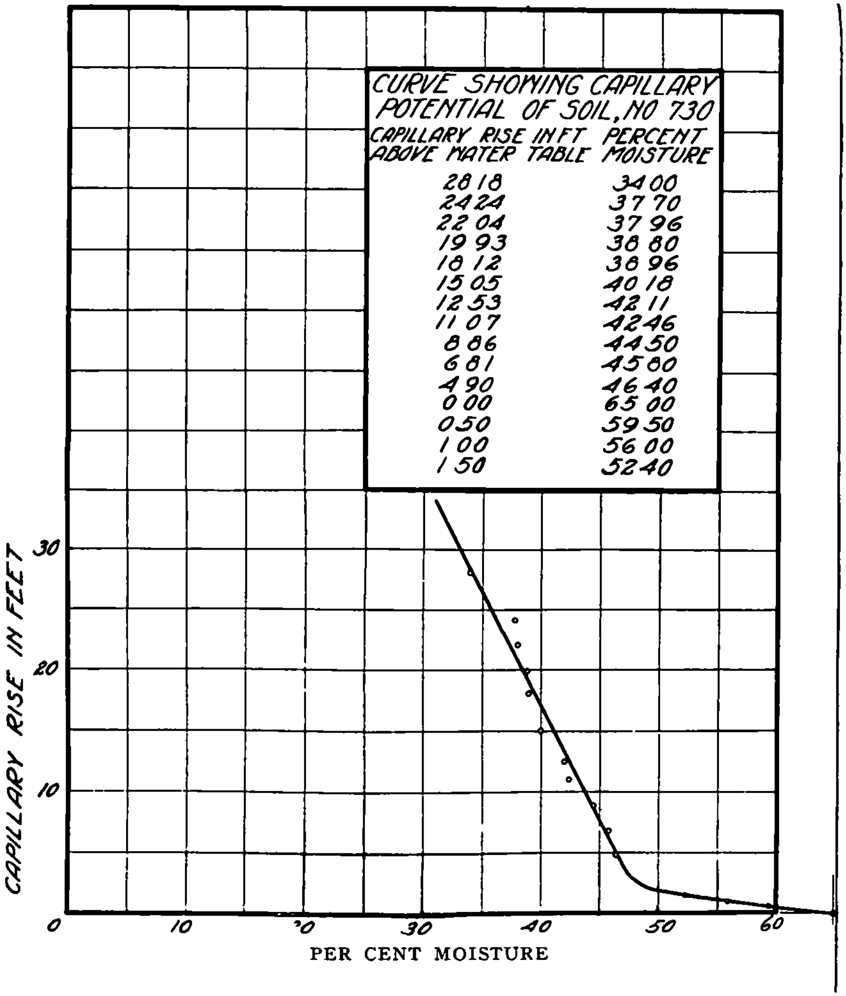


Figure 5—Apparatus for determining capillary potential of soils

air tight by means of a water seal, and the lower end of the water column set barely below the surface of a cup of mercury.

Upon evaporation of moisture from the surface of the soil, water is pulled from the capillary tube into the soil, tending to produce a vacuum at the lower end of the water column. As the water in the capillary tube is lifted, the mercury, due to atmospheric pressure, follows until a point is reached where the combined weight of water and mercury are in equilibrium with the capillary power of the soil. Further evaporation from the soil allows air to penetrate the soil pores, and the column of mercury drops.

Since it is obvious that variations in atmospheric pressure must be considered, all determinations are corrected to a pressure of 30 inches of

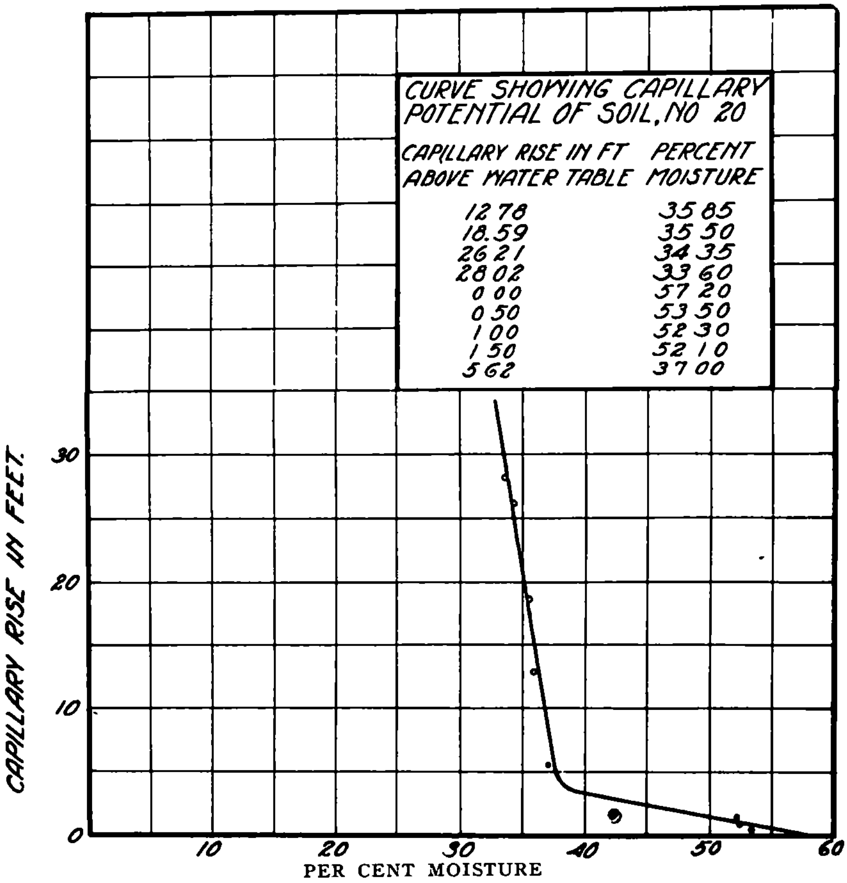


CAPILLARY RISE IN FT ABOVE WATER TABLE	PERCENT MOISTURE
28 18	34 00
24 24	37 70
22 04	37 96
19 93	38 80
18 12	38 96
15 05	40 18
12 53	42 11
11 07	42 46
8 86	44 50
6 81	45 80
4 90	46 40
0 00	65 00
0 50	59 50
1 00	56 00
1 50	52 40

Figure 6

mercury By determining the percentage of moisture held in the soil under different columns of mercury, the rate of change in the capillary moisture may be obtained With the percentage of capillary moisture held at a certain height and the rate of change in this moisture both known, it is possible to compute the total capillary rise

Figure 6 shows the percentage of moisture held in Susquehanna clay at several heights above the water table, as determined by this laboratory test This is a stiff, tenacious, red clay and occupies hills and rolling areas on the inner border of the Atlantic Coastal Plain region



CAPILLARY RISE IN FT ABOVE WATER TABLE	PERCENT MOISTURE
12 78	35 85
18.59	35 50
26 21	34 35
28 02	33 60
0 00	57 20
0 50	53 50
1 00	52 30
1 50	52 10
5 62	37 00

Figure 7

Figure 7 was obtained from tests on soil No 20, a Willows clay adobe soil from near Willows, Glenn County, California This is a dense, compact, dark chocolate-brown clay of adobe structure It becomes very sticky when wet, puddles readily, and bakes upon exposure during droughts It will be observed that the upper part of this curve is almost vertical indicating an extremely low decrease in capillary moisture per foot above the water table The rate of decrease in capillary moisture is 0 165 per cent per foot above the water table, which is the second lowest rate of any soil tested

Figure 8 shows a capillary moisture curve obtained from soil No 1236, which is a loose soil from Iowa This soil has a decrease in capillary moisture of 0 711 per cent per foot of rise above the water table, which represents almost the upper limit of moisture change of any soil tested

It will be observed that all of the capillary moisture curves presented show a decided change in direction at a mean height of approximately 3½ feet above the water table The reason for this is not fully understood, but the following explanation seems reasonable and is offered as the major cause for this marked change

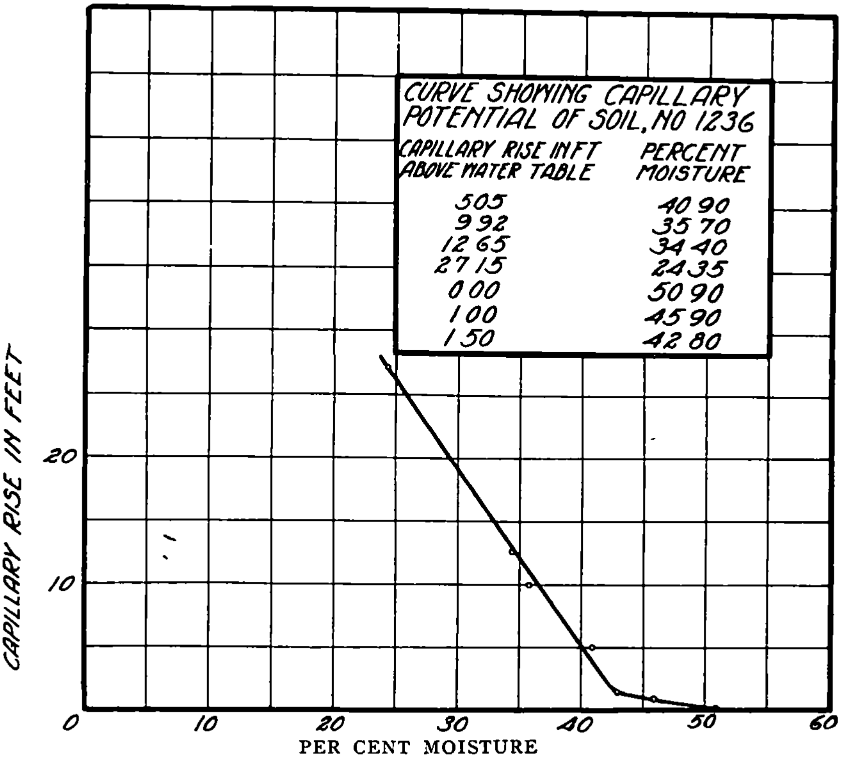


Figure 8

Figure 8 shows soil No 1236 tested for percentage of capillary moisture held at 1 00, 1 50, 5 05, 9 92 12 65 and 27 15 feet above the water table, and for water capacity when the surface of the soil is submerged one millimeter below the water table In the submerged condition the void spaces in the soil must be more than filled with water and the moisture film surrounding the individual particles is sufficiently thick to separate these particles At an elevation of one foot the weight of the

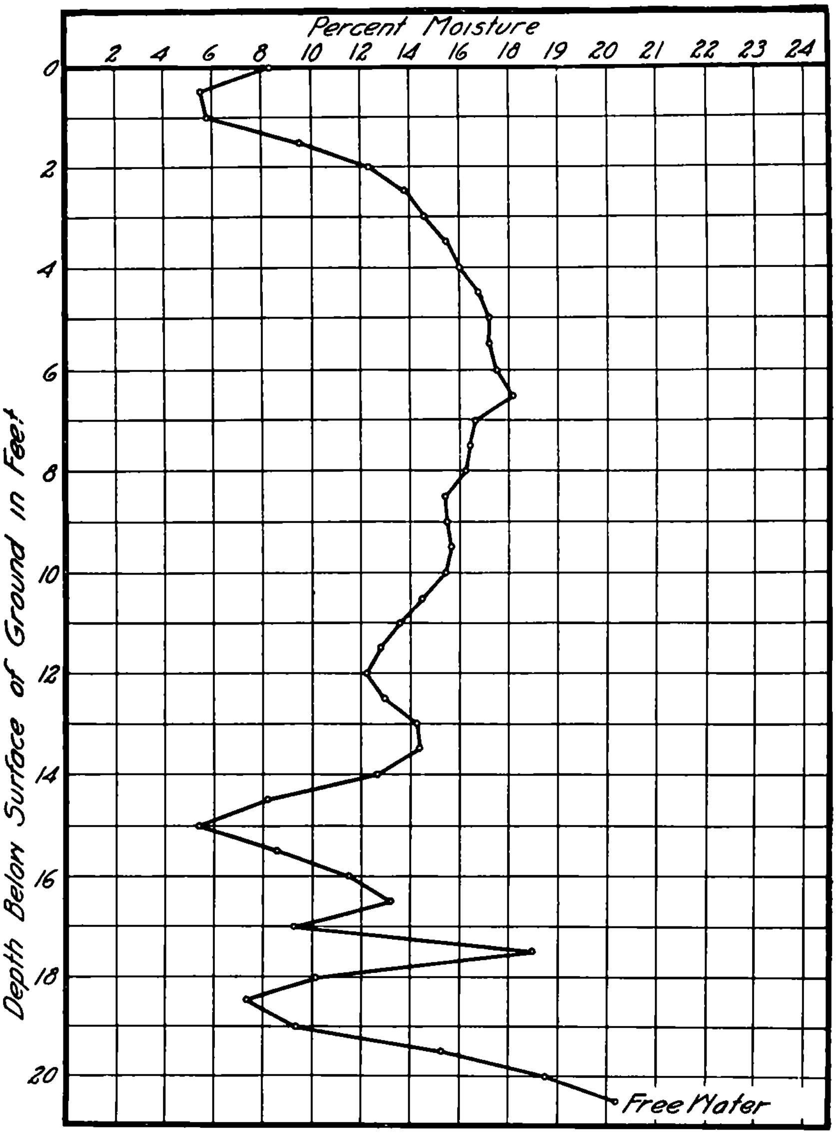


Figure 9—Moisture determinations in soil covered with grass Arlington Experiment Farm. Borings made July 27, 1925, at Point 2, Ten feet east of Point 1

water is apparently sufficient to force the soil particles somewhat closer together, thereby reducing the thickness of the moisture film surrounding the soil particles, and at an elevation of 1½ feet the arrangement of soil particles apparently remains unchanged even under a weight of 27 feet of water

It is believed that at or near the edges of fills where the foot is contiguous to the water table, a capillary moisture curve would be similar

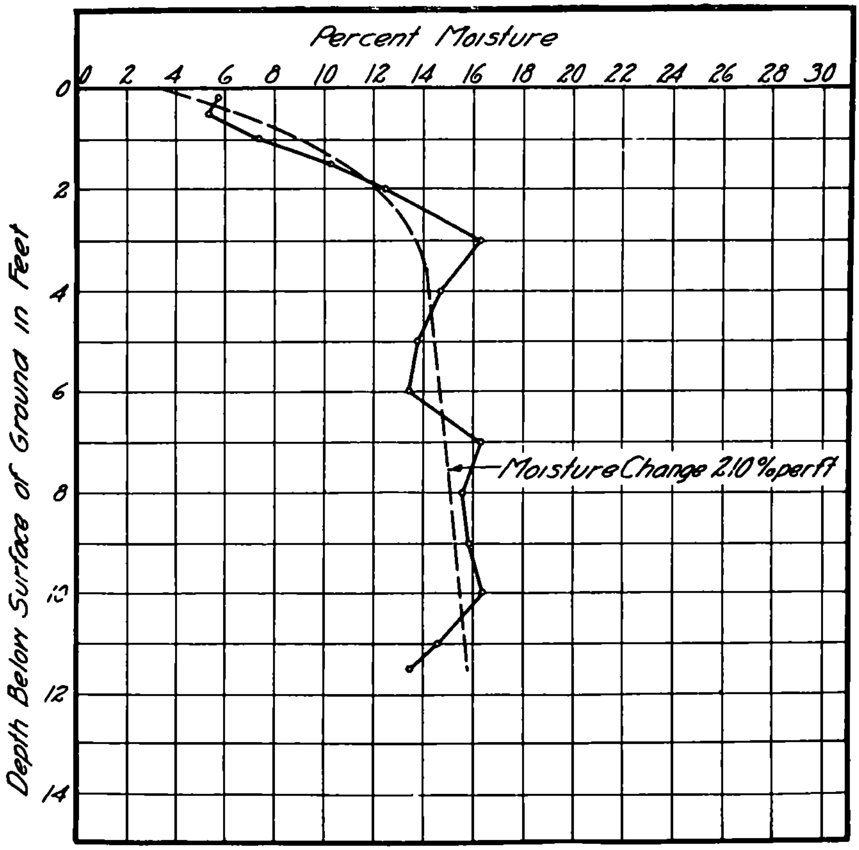


Figure 10—Moisture determinations in soil covered with grass. Arlington Experiment Farm. Borings made July 16, 1925, at Point 1

in form to those here presented, but that nearer the center of the fill the curve would be a straight line, intersecting the line of zero elevation somewhat to the left of the 45 per cent moisture line Since all of these determinations were made under a condition in which the soil is free to evaporate only at the top surface, the above statement applies only to a fill the sides of which were sealed against evaporation but whose subgrade could lose moisture by evaporation

Table I shows the capillary rise, rate of change in moisture content above the water table, percentage of capillary moisture held at certain heights, and the computed total capillary moisture in the several soils The computations are based on the assumption that the soil out in the field is identical in structure and temperature with the sample tested For the purpose of determining the relation between the capillary moisture change due to gravity only in the soil as it exists in place and as determined by the mercury method in the laboratory, the following tests have been made

Two points were selected on the Arlington Farm where soil conditions to a depth of several feet were believed to be as uniform as could be found in this vicinity, borings were made, samples for moisture taken, and the results plotted as shown in Figures 9, 10 and 11

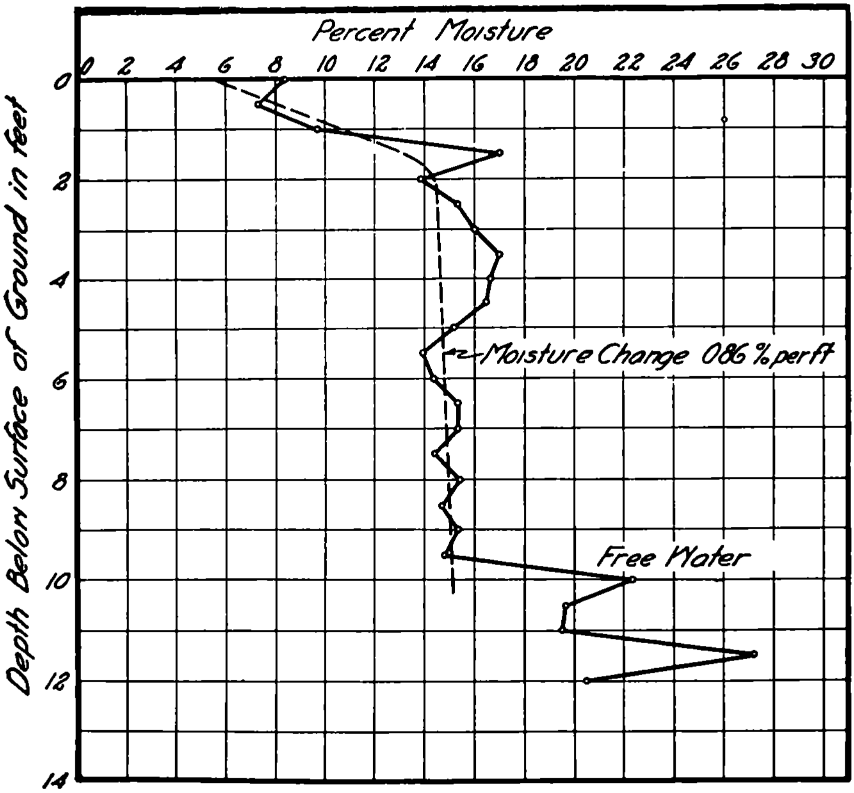


Figure 11—Moisture determinations in soil covered with grass. Arlington Experiment Farm Borings made July 30, 1925, at Point 3

As would be expected, the points do not lie on a straight line There are changes in the soil and each change has its own capillary potential which produces a more or less zigzag line All three of the curves indicate centers of increased moisture with some evidence of capillary movement from these points Figures 10 and 11, on the whole, indicate the effect of gravity and show a decreasing percentage of capillary moisture above free water The decrease as shown in Figure 11 seems to be somewhat low for soils of this type, while that in Figure 10 compares more favorably with the laboratory tests on soils of similar type

Recent tests made by the Bureau of Public Roads at the Arlington Experiment Station on the permeability of soils show that the rate of percolation of water through fine sand whose temperature is 32° F is only

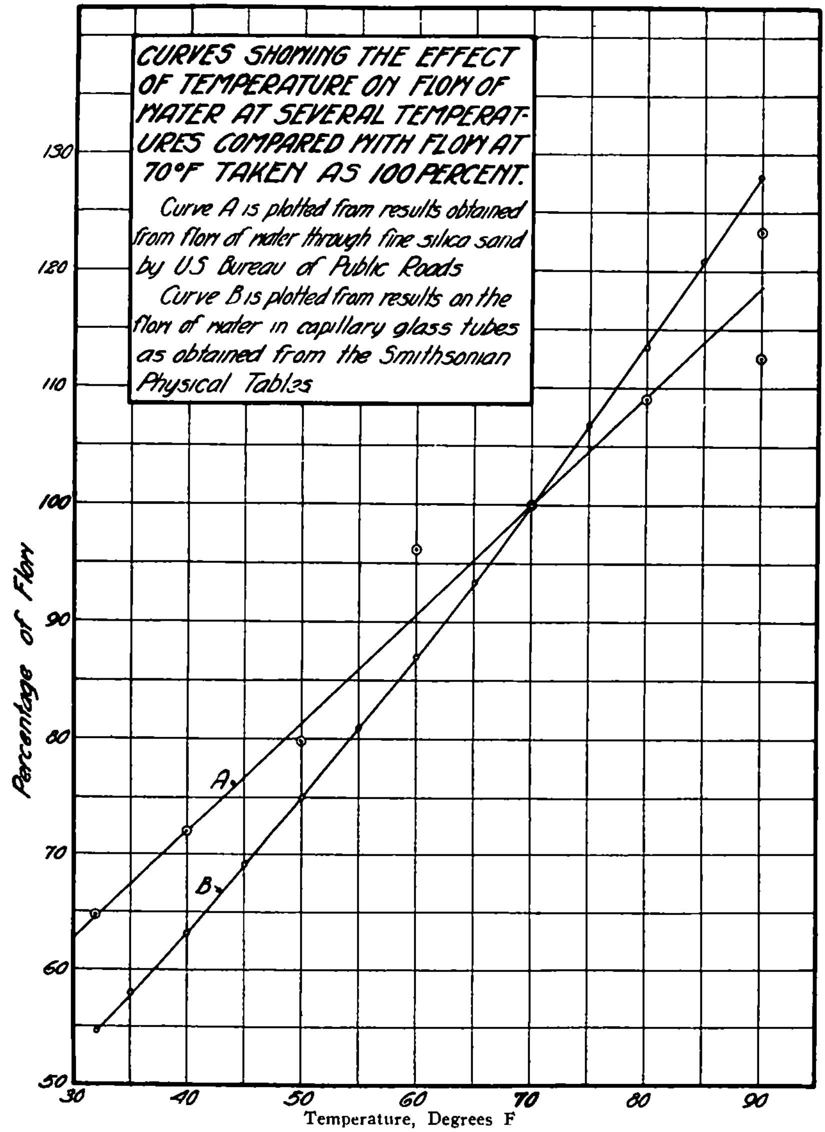


Figure 12

65 per cent of its rate at 70° F Tests made by the Bureau of Standards on the viscosity of water in capillary tubes agree quite closely with these figures Figure 12 is a curve which shows the relation between temperature and flow of water This illustration is a very striking one and shows the enormous increase in the viscosity of water with its decrease in temperature

TABLE I
CAPILLARITY OF SOILS

Soil No	Capillary rise in feet	Percentage capillary moisture at height shown	Percentage moisture change per foot	Computed possible capillarity rise in feet
1434	22 12	9 18	0 324	50 4
1435	24 12	36 94	0 387	124 7
1439	29 20	23 20	0 458	79 9
20	28 02	33 60	0 165	231 0
730	28 18	34 00	0 530	92 3
1236	27 15	24 35	0 711	61 3
A	5 50	32 48	0 455	71 3
B	1 73	31 20		
C	0 99	29 90		
D	0 25	18 80		
E	0 16	18 60		

NOTE Soils A to E are pure quartz of the following sieve sizes

A	passing	200 mesh
B	"	100–200 mesh
C	"	60–100 mesh
D	"	20– 60 mesh
E	"	20– 30 mesh (standard Ottawa sand)

Hilgard and Loughbridge[1] found that the change in percentage of capillary moisture in three soils was as follows

Sandy soil, 11 28 per cent per foot above the water table
Sandy alluvial soil, 8 76 per cent per foot above the water table
Adobe soil, 10 44 per cent per foot above the water table

Curves showing the distribution of moisture in the above soils are given in Figure 13

It is quite apparent that there is considerable evaporation near the top of the adobe soil, No 1679 This is evidenced by the curve swinging to the left toward the top, otherwise the line would be straight, provided the soil was uniform in quality, compaction, etc The high moisture change per foot above the water table is probably due to evaporation loss throughout the column These tests were made in copper tubes 1 inch in diameter, divided into segments 6 inches long, and flattened on one side In the flattened side a slot half an inch wide was left and glass plates, held in position by rubber bands, were cemented on the slotted side by means of paraffine to prevent the sifting of the soil

If these tubes were not airtight at the joints and at the slotted sides,

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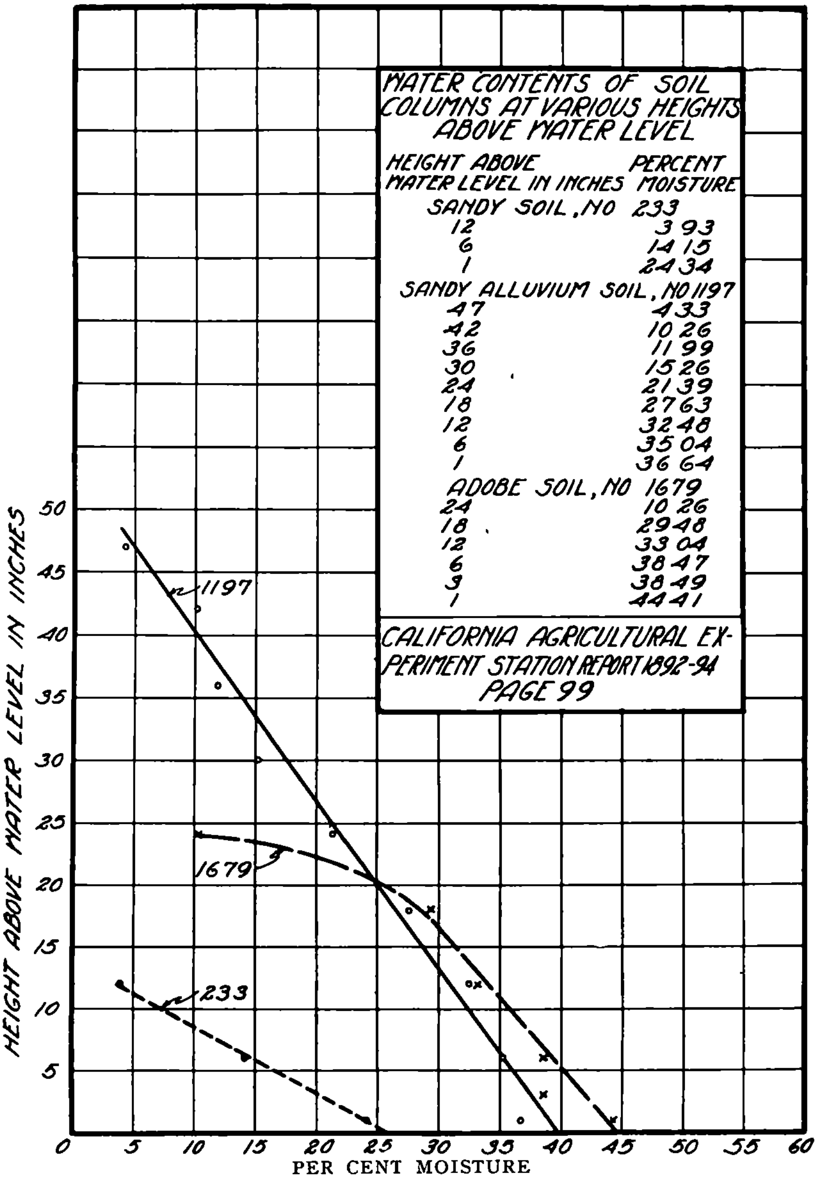
[1] California Agricultural Experiment Station Report 1892–4, p 99



WATER CONTENTS OF SOIL COLUMNS AT VARIOUS HEIGHTS ABOVE WATER LEVEL

HEIGHT ABOVE WATER LEVEL IN INCHES	PERCENT MOISTURE
SANDY SOIL, NO 233	
12	3 93
6	14 15
1	24 34
SANDY ALLUVIUM SOIL, NO 1197	
47	4 33
42	10 26
36	11 99
30	15 26
24	21 39
18	27 63
12	32 48
6	35 04
1	36 64
ADOBE SOIL, NO 1679	
24	10 26
18	29 48
12	33 04
6	38 47
3	38 49
1	44 41

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Figure 13

evaporation would undoubtedly occur through the soil column and would account for the high moisture change

It is believed that the mercury method outlined will give an accurate measure of the capillary potential of soils under maximum conditions In level or rolling soils no evaporation can occur except at the surface, but on fills and steep slopes evaporation losses from the sides reduce the percentage of capillary moisture very largely, and under these conditions large corrections must be made It is a well-known fact that in sections of the semi-arid west where no rain falls from early spring until late fall, crops are produced The depth to free water in this section, as evidenced by wells, ranges from 75 to 200 feet, and it is believed that moisture is carried by capillary action from the water table at these great depths to the plants at the surface

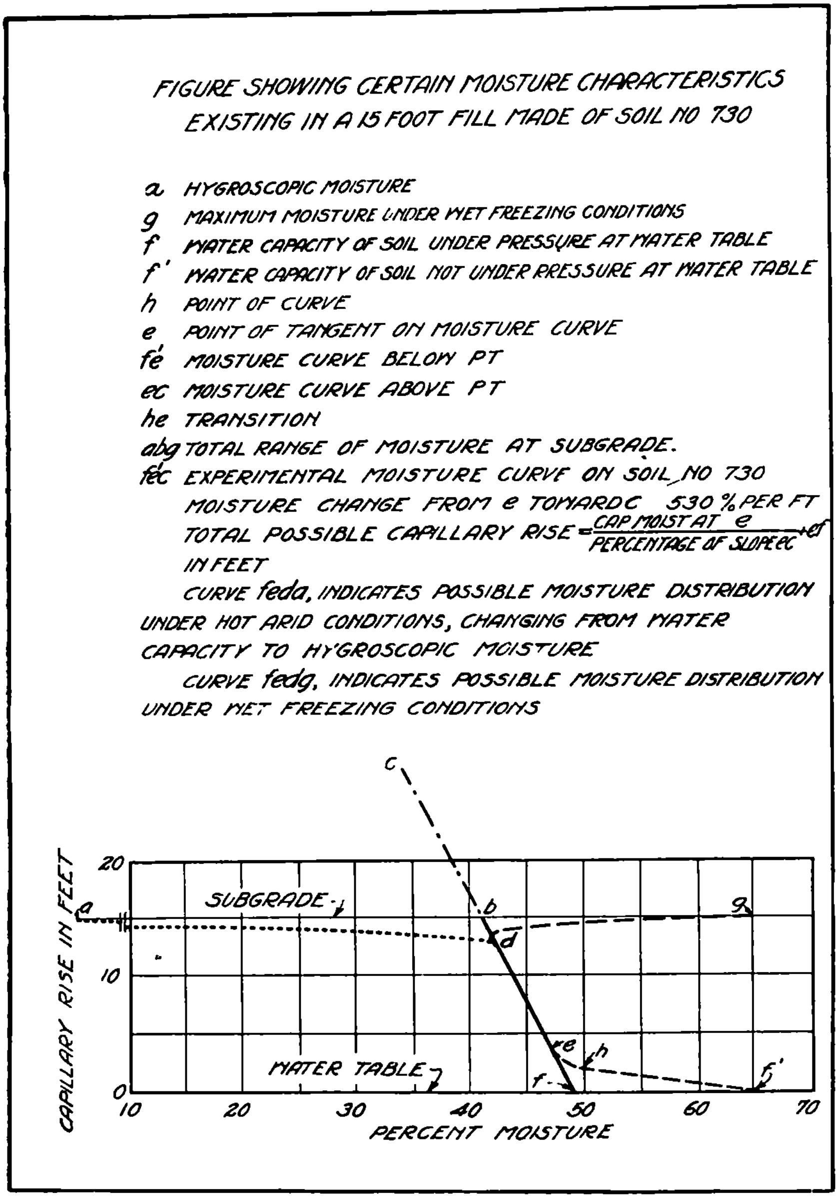

FIGURE SHOWING CERTAIN MOISTURE CHARACTERISTICS EXISTING IN A 15 FOOT FILL MADE OF SOIL NO 730

a HYGROSCOPIC MOISTURE
g MAXIMUM MOISTURE UNDER WET FREEZING CONDITIONS
f WATER CAPACITY OF SOIL UNDER PRESSURE AT WATER TABLE
f' WATER CAPACITY OF SOIL NOT UNDER PRESSURE AT WATER TABLE
h POINT OF CURVE
e POINT OF TANGENT ON MOISTURE CURVE
fe' MOISTURE CURVE BELOW PT
ec MOISTURE CURVE ABOVE PT
he TRANSITION
abg TOTAL RANGE OF MOISTURE AT SUBGRADE.
fe'c EXPERIMENTAL MOISTURE CURVE ON SOIL NO 730
MOISTURE CHANGE FROM e TOWARD C 530 % PER FT
TOTAL POSSIBLE CAPILLARY RISE $= \frac{\text{CAP MOIST AT } e}{\text{PERCENTAGE OF SLOPE } ec} + ef$ IN FEET

CURVE feda, INDICATES POSSIBLE MOISTURE DISTRIBUTION UNDER HOT ARID CONDITIONS, CHANGING FROM WATER CAPACITY TO HYGROSCOPIC MOISTURE

CURVE fedg, INDICATES POSSIBLE MOISTURE DISTRIBUTION UNDER WET FREEZING CONDITIONS

Figure 14

The method of measuring the capillary potential of soils in soil-filled tubes is inadequate, slow, and gives little information The mercury method, on the other hand, is rapid, gives apparently a truer indication of the effect of gravity on the thickness of the capillary film, and at least gives a truer conception of the height of capillary travel in different soils

EFFECT OF TEMPERATURE, ELEVATION AND PRESSURE ON CAPILLARY MOISTURE

The value of increasing the height of a fill for the purpose of lowering the percentage of capillary moisture at the top is a moot question The factors involved are the capillary potential of the soil, evaporation and height above the water table Usually the more important of these three factors are capillary potential and evaporation

Suppose a fill is to be constructed across a low plain whose water table is contiguous to the surface of the ground If the fill were built of soil No 730, a Susquehanna clay, uniform in texture and compaction, and having the surface of its side slopes sealed against the penetration of air and the evaporation of moisture and with the subgrade 15 feet above the water table, the percentgae held in the soil would be as shown in Curve *f e b* in Figure 14 Under hot and arid conditions the curve would be similar to *f e d a*, that is, it would change from water capacity under fill pressure at the water table and decresae to hygroscopic moisture at the top of the fill Under certain conditions of moisture and freezing the curve would be similar to *f e d g*, i e , changing from water capacity under fill pressure at the water table to the capillary moisture of *d*, still further decreasing in moisture until the lower depth of freezing is reached and then rapidly increasing in moisture until the water capacity is again reached at the sufrace

The effect of the force of gravity and low temperature on the thickness of a capillary film surrounding soil particles may be illustrated by Figure 15 This figure shows that there is a uniform reduction in the thickness of the capillary film from the surface of a recent water table at C toward B This is due to the tendency of the capillary film to flow under its weight toward the hanging drops at the lower end of the column at C and explains the uniform rate of decrease in the percentage of capillary moisture held as the height above the water table increases If there is an increase in the temperature of the soil from B to A, there will be a still further decrease in the thickness of capillary film due to increased vapor pressure of this water film

Should there be a decrease in the temperature of the upper part of the soil columns, there would be a thickening of the capillary film and at the freezing point the soil would be completely saturated in the upper surface of the soil column, provided the rate of freezing had not been

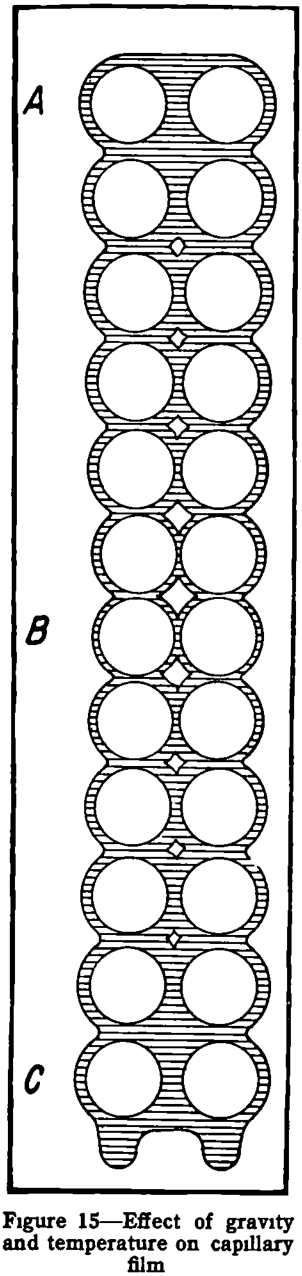

Figure 15—Effect of gravity and temperature on capillary film

too rapid and the entire soil column is fully charged with capillary moisture

Thus it will be seen that the soil under discussion having a capillary moisture change of only 0 53 per cent per foot above the water table, little will be gained in the reduction of capillary moisture by increasing the height of the fill very much above the water table It is therefore believed that any decrease in moisture below 0 53 per cent per foot will be due to increasing the area of exposed fill so that greater opportunity for evaporation may be given

Evaporation is a powerful factor in drying all soils, but it is one about which little is known in definite terms Even from a casual observation on roads having widely different degrees of exposure to sun and wind, which are the most powerful evaporating agencies, some general measure of this one factor may be obtained The most important factor in evaporation of water from soils is soil temperature There are other factors of importance, but there is little available information which enables one to evaluate any of these factors

Increasing the height of fills above the water table or above the adjacent ground exposes a much greater soil surface to the evaporating forces In narrow fills it is believed that much would be gained, but in wide fills, such as are made for modern roads, the writer doubts the wisdom of raising the height of the fill much in excess of the requirements for proper drainage

Vaporization and Condensation —There is a very close association between the capillary and vaporized forms of moisture As the capillary film rises above the water table, the water film which covers the soil particles becomes thinner. At the same time this capillary film is covered by a film of vapor, provided the temperature of the soil air is above the dew point under the existing humidity in the soil voids If the temperature of the soil air drops to or below the dew point, there will be condensation Therefore, water may be moving upward at one depth in the soil under surface tension and at another depth under vapor pressure, while at some other depth the water vapor is being condensed on the soil particles

It is known that under freezing conditions excessive moisture collects in clay soils in the upper stratum adjacent to the pavement and frequently produces failure of the pavement Sections where alternate freezing and thawing occurs to a depth somewhat greater than the thickness of the pavement apparently suffer most Unquestionably much of this comes from the condensation of water vapors from below. When freezing has advanced deep enough to arrest capillary or vapor movements, the deposition of moisture ceases and may be actually evaporated to dryness during periods of low precipitation (The writer has observed this condition in northern Minnesota)

Where climatological conditions are such that freezing never reaches the bottom of pavements, it is not believed that condensation will ever occur to such an extent as will be noticeable Where freezing penetrates to or below the surface of the subgrade, condensation will certainly occur on the heavier clay soils Such freezing, when accompanied by sufficient precipitation and heavy truck or motor bus traffic will certainly produce subgrade failures on the heavier and more intractable clays unless the subgrade is specially drained and aerated or the pavement is strengthened

Treatment for Wet Cuts —While it is generally presupposed that all wet cuts are drained when constructed, yet experience has taught that this is far from true Cuts in which perennial springs are encountered are almost invariably drained, but cuts in which seepage or free water flows for a short period near the close of periods of high precipitation are common almost everywhere The general appearance and characteristics of wet cuts have been described under "Gravitational Water "

Borings should be made for the purpose of determining the uniformity of the subgrade soil, where there are considerable variations in the soil structure, such as strata of sand, gravel or impervious clay Figure 2 shows such a condition in a cut and fill section In this case the seasonal flow of water is at right angles to the roadway, but such conditions are very frequently seen where the flow is parallel to the center line of the road Failures are frequent and occur at points where such strata are intersected by the plane of the subgrade Such failures may be observed on many grades The method of cure is simple, but effective

Figure 16 shows a form of the only known effective method to pursue. Where the line of flow is parallel to the center line of the road, transverse drainage should be so placed that the water will be intercepted before reaching the base of the pavement

It is suggested that surveys of subgrade soil moisture conditions be made near the close of periods of high precipitation, such as usually occur in the winter or early spring This will locate the wet spots and make possible the proper drainage or treatment This survey should also record the depth of all side drains with reference to the subgrade and should show needed drainage improvements

Treatment of Soils Having a High Capillary Potential —Heavy clay soils such as encountered in many sections should be treated, especially when found at considerable elevations, or where the winter temperatures are severe and where snowfall is heavier than it is in some of the more sheltered valleys The higher elevations, when located on the northern or shaded sides of the mountain, will suffer most from moisture and freezing, and it is in such locations that extreme caution must be exercised when heavy clays are encountered

If there are any evidences of seepage from the sides of cuts—and such evidences usually do exist at times—it should be intercepted by tile and crushed stone drainage laid below the frost line and a blanket layer of granular materials placed on the subgrade as shown in Figure 16 Such materials as sand, gravel, cinders, granulated slag and stone screenings meet the requirements splendidly Crushed stone is also good, but a blanket layer of any of the above mentioned materials, having filtering qualities, must be interposed between the crushed stone and the clay to prevent the passage of clay into the voids of the stone The thickness of this layer of fine material must be somewhat greater than the effective size of the voids in the stone

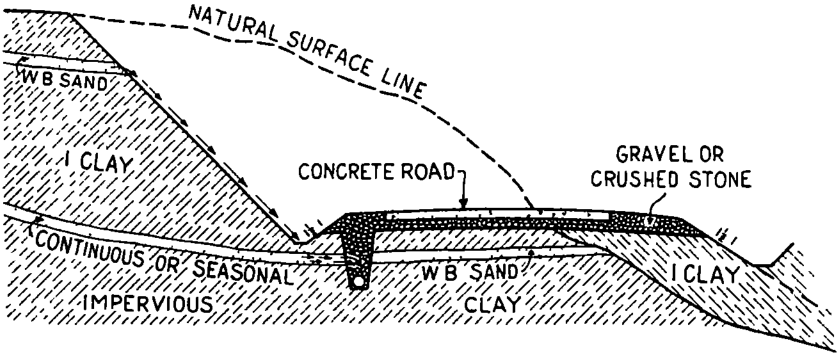

Figure 16—Method of intercepting seepage from sides of cuts

When using such treatments, they must be extended out through the shoulders for the purpose of drainage and ventilation or water will be retained under the pavement and the purpose of the treatment thwarted. In all cases the subgrade should be crowned so as to aid rapid drainage

Influence of Climate on Subgrade Conditions —The influence of climate on the moisture content of soils must be considered in connection with soil characteristics. The moisture-holding capacity increases as its temperature is lowered Soil drainage under winter conditions is far less active than under summer temperatures with equal precipitation Since the viscosity of water changes inversely with its temperature, this explains in part why cold soils drain more slowly than warm

Figure 12 shows curves made from data taken from Smithsonian Physical Tables showing the viscosity of water in capillary tubes at temperatures of from 32° F to 90° F, and from experiments made in

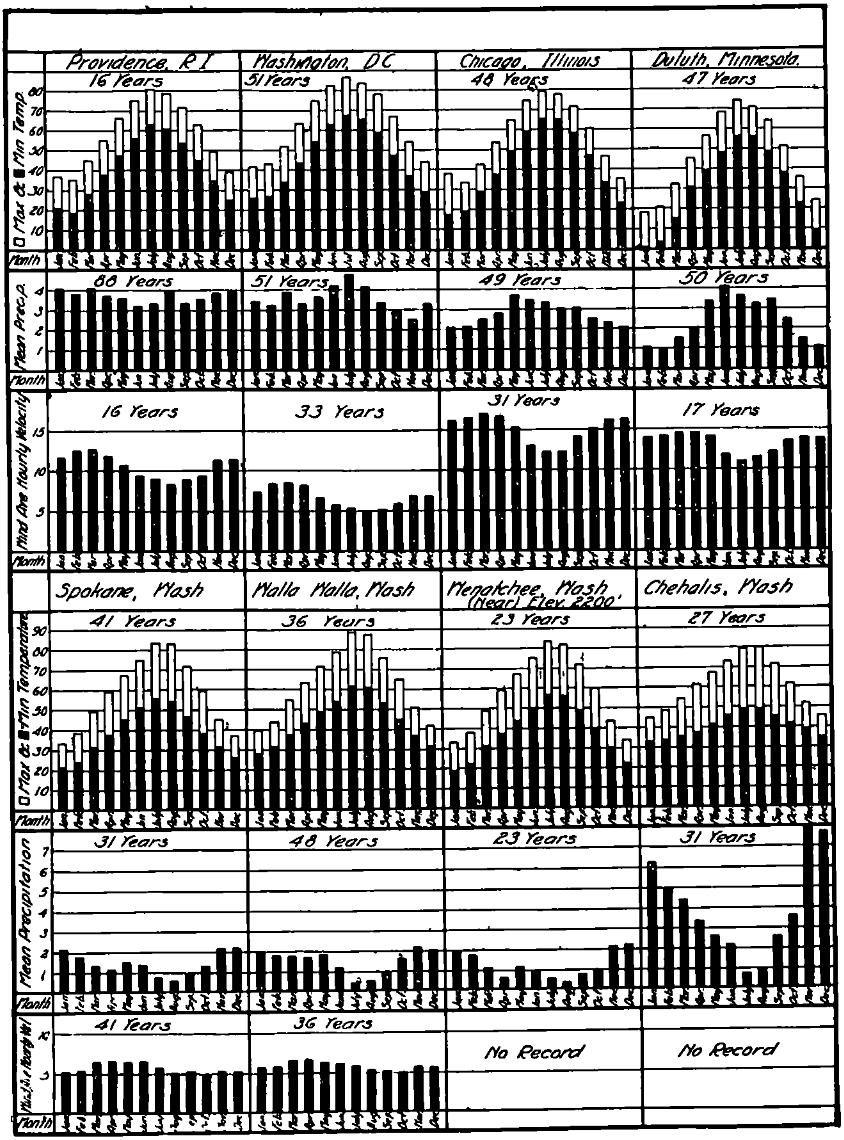

Figure 17—Variations in climate in different sections

the subgrade soil laboratory of the U S Bureau of Public Roads on the rate of percolation of distilled water through clean, fine silica sand through the same temperature range

To illustrate the variation and types of climate in certain parts of our country Figure 17 is presented

Due to the low winter temperature and high winter rainfall in Providence, Rhode Island, similar subgrade soils would react very differently from those of Chehalis, Washington, where the winter temperature is milder Subgrade soils near Chehalis, Washington, subjected to such great extremes of moisture are much more likely to fail from volume change than a similar soil near Providence

Duluth, Minnesota, with extremely low winter temperatures, has a low winter precipitation and the writer has seen subgrades in April almost bone dry High winds, low precipitation, and with capillary action arrested by solidly frozen subgrades, had made it possible for evaporation to remove excess water from the subgrade Such a climate as that of Duluth is not conducive to excessive volume change in subgrade soils The low winter temperatures coupled with the movement of water through glacial deposits produces heaves and pavement ruptures which are appalling Drainage under such frost conditions presents a problem difficult of solution

SUMMARY OF CONCLUSIONS

Subgrade Soils

1 Ideal subgrade soils
    a Good internal drainage
    b Low volume change
    c Uniform structure and color
    d High percentage of crystalline material
    e Low moisture retaining capacity
    f High bearing value
2 Undesirable subgrade soils
    a Dense, close-textured and difficult to drain
    b High volume change
    c Variable in structure and often times mottled in color
    d High percentage of amorphous materials
    e High moisture-retaining capacity
    f Low or variable bearing value

The Movement of Surface Water

1 Roadway should be protected from slopes
2 Snow, litter and debris should be removed from gutters, and outlets should be frequent

Movement of Ground Water

Gravitational Water

1 Enters subgrade through
    - a Cracks in pavement and at edges
    - b Joints and cracks in subgrade soil
    - c Porous areas and water-bearing strata
2 Held in subgrade soil by
    - a Character of soil
    - b Compact layers
    - c Viscosity of water due to low temperature

Capillary Water

1 Height of capillary rise in inverse proportion to size of soil pores

2 Percentage of moisture held in a uniform soil column decreases uniformly as the height above the water table is increased

3 Known factors governing the capillary potential are
    - a Size of pores
    - b Chemical and physical character of soil particles
    - c Temperature of soil
    - d Moisture of soil
    - e Barometric pressure
    - f Humidity of outside air

Vaporization and Condensation

1 Water in the capillary form may be converted directly into either the vaporized or gravitational form by change of temperature or pressure

2 Soils may become completely saturated by the combined forces of capillarity, vaporization, and condensation

3 Cold and dry climates tend to produce dry subgrades, provided the subgrade soil is uniform in structure and remains frozen to considerable depth

Treatment for Wet Cuts

1 Intercept perennial or seasonal seepage

2 Locate and tap compacted layers of soil and clay pan

3. Promote aeration and drainage of the subgrade soil by the use of suitable layers of such granular materials as coarse sand, gravel, crushed stone, slag, cinders, etc , having filtering qualities, with frequent drainage outlets

Treatment of Soils Having a High Capillary Potential

1 Keep water table as low as permissible
2 Promote aeration and drainage by the use of layers of granular materials having filtering qualities
3 Cut back trees so as to give the fullest exposure of the roadway to the sun and wind

Influence of Climate on Subgrade Conditions

1 Under the most favorable climate few subgrade soils fail
2 Favorable climates for stable subgrades are
    a Those having low precipitation during winter and copious summer precipitation
    b Those having scanty precipitation throughout the year
3 The most unfavorable climates for stable subgrades are
    a Those having wide seasonal variations in precipitation
    b Those having high precipitation during freezing periods
    c Frequent alternate freezing and thawing

STRESS MEASUREMENTS IN CONCRETE PAVEMENTS

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The first requirement in the design of a concrete pavement is that it shall safely carry such traffic as may legally be placed upon it It is therefore necessary that the designing engineer know what stresses the various wheel loads will produce in a given design of pavement, and it is equally necessary that the legislator know what loads may be safely allowed on concrete pavements already built This is one of the big problems in highway research today

The U S Bureau of Public Roads has attacked this problem by the development of a method for accurately measuring the deformation produced by traffic in the fibers of a concrete road slab for determining from these deformations the magnitude of the resultant stress This method has been used with considerable success in a number of investigations and it is the purpose of this paper to describe the method and to show its practical application to the determination of stresses in concrete pavements due to traffic loads

In order to measure the small deformations occurring in concrete at or near a wheel load, it is necessary to have a compact recording strain gage of high magnification Such a gage, designed and developed for this purpose, was described in the Proceedings of the Fourth Annual Meeting of the Highway Research Board Essentially, the gage consists of a bell crank lever whose ratio is approximately 70 to 1 This multiplied movement is recorded by a stylus on a smoked glass plate