Variation in temperature would be most marked near the surface of the ground or at the underside of the pavement, and when sufficient water has accumulated, it would migrate downward by drainage or by capillary action. It is not clear, however, whether the water vapor characteristically migrates upward from a submerged water-table (which may be many feet below the surface) or whether it is carried in by the movement of air from the outside atmosphere, or both.

A proven answer to these questions will clarify the problem of designing preventive or corrective methods and should enable the highway engineer to proceed with much greater intelligence or assurance than is possible at the present time.

The charts illustrate some of the relationships between the characteristics of the soil and the amount of moisture found in the soil immediately beneath Portland cement concrete pavements in California.

As a part of the investigation, holes were bored in the concrete pavement using an 8-in. diamond bit, and samples of the underlying subgrade soil were taken for a depth of 24 in.

Separate samples were secured for each 6 in. beneath the pavement and the density in place of the first two layers was determined by the sand volume method whenever possible.

Figures 1 to 5, inclusive, illustrate the typical types of moisture distribution. Figures 1 to 4 represent borings where the soil was of the same character for the entire depth. Figures 6, 7, and 8 show other soil moisture relationships.

SOIL MOISTURE UNDER THE CONCRETE PAVEMENT OF AN AIRPORT

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During the spring of 1949 samples were taken of the earth layers under and adjacent to the concrete pavement of an 80 m. (262 ft.) wide runway and a 15-m. (49-ft.) taxi drive. The airport is situated on a slightly inclined river deposit. The results of the sieve analyses are given in Figure 3. The size of particles varies greatly, but the material consists chiefly of sandy silt and silty sand-gravel. The great variation in particle-size can be explained by the river having changed its course during times past.

During the occupation of Norway by Germany, German geologists made investigations of the soil of this airport. The results show that there are radical variations in the soil also at other locations on this site. It is not possible to define the soil by definite strata.

The concrete pavement is about 15 cm (6 in. thick, laid during 1940-42). It is, at present, impossible to ascertain the exact date. The pavement is in good condition and the joints filled with asphalt. It is therefore assumed that no appreciable seepage of surface water into the ground can occur. The pavement is poured directly on the subgrade without any base-course.

The samples are taken along an expansion joint across the pavement of the runway and taxi drive. The location of the test holes will appear from Figures 1 and 2. The test holes of the runway are labeled A_0 to A_9. From each hole are taken 4 or 5 samples at a difference in elevation of about 0.25 m (10 in.). The samples are numbered from the top. For the taxi drive the test holes are labeled similarly B_1 to B_6. The test hole elevations are tied in to arbitrary bench marks different for the two profiles. They show proper relations for each profile but there is no relation between the two.

According to observations made by the Germans the ground-water level is assumed to be about 2.0 m (6.55 ft.) beneath the surface of profile A and about 9.0 m (29.5 ft.) for profile B. There seems to be some uncertainty with regard to the ground-water level at profile B, but it is certain that it could not possibly be higher than 5 - 7 m (16 - 23 ft.) beneath the surface.

Profile A is located 11.0 m (36 ft.) from the end of the pavement. Profile B is far from the end.

Under the assumption that the pavement is waterproof there can be no surface water seeping through to the ground underneath.

The soil beneath the pavement can therefore receive moisture only in one of the

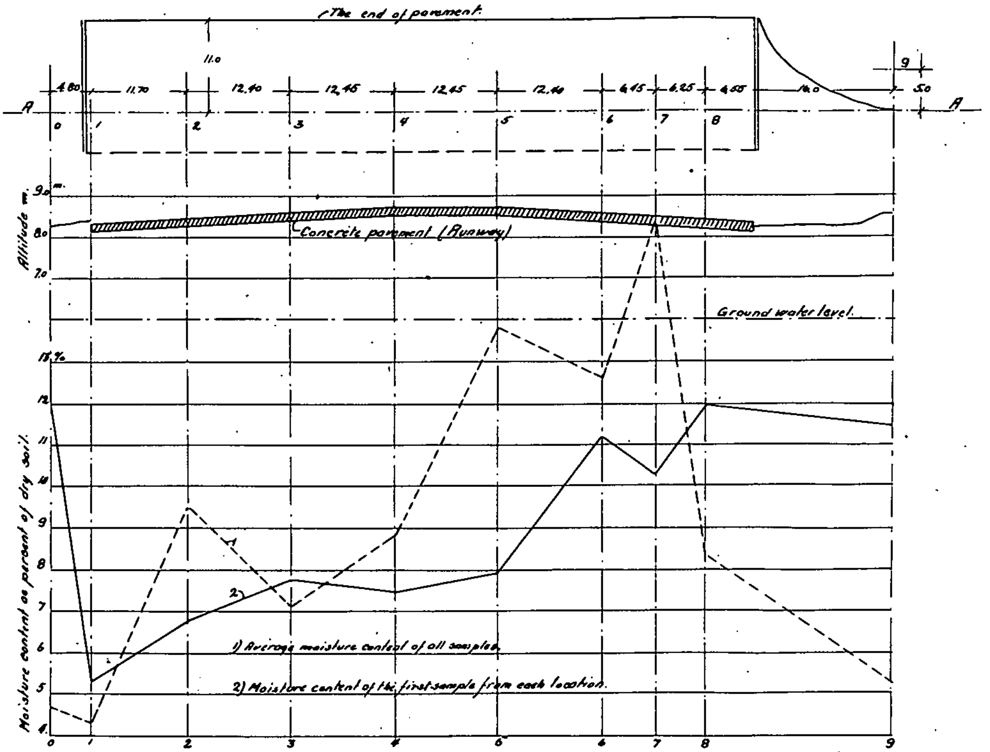

Figure 1. The figure shows the location where the test holes A_0 - A_9 were taken. The curves indicate the initial water content of the samples.

following ways:

(1) By capillary action from the earth masses lying outside the pavement having absorbed precipitation.

(2) By capillary action from the ground water, the assumption being that the capillary head of the earth is equal to or greater than the distance to the ground water.

(3) By condensation on the under side of the pavement. The vapor must have originated in the deeper strata under a temperature higher than that of the pavement. Condensation will consequently only occur under certain weather conditions.

(4) By water from melting ice in soil sensitive to frost. Considerable quantities of moisture are often developed in this manner.

Water from condensation will usually assert itself by higher moisture content in samples taken immediately underneath the concrete pavement.

In Figures 1 and 2 are curves showing the initial water content of the top samples. A curve showing the average water content of all samples is also drawn. In profile A the water content of the top samples are, in general, higher than the average. This is particularly the case for the right-hand portion.

As can be seen in Table I, the material in the right-hand portion is generally more fine-grained than to the left. This is presumably the principal reason for the higher water content. The same relations are also found in samples taken from deeper strata where condensation-water hardly could occur. In Figure 2 are similary shown the same relations for profile B. Table II is compiled with the same symbols as those used in Table I.

In Table II, B_3. 1 showing the highest water content can also be seen to contain the most fine-grained material. In this case it is assumed that condensation-water has played no part whatever.

Water from melting ice in frost-sensitive soil can cause a complete soaking of the

TABLE I

Ratio Silt + Fine Sand: Sand = α, the Water Content β and Permeability μ Given for Top Samples of All Test Holes in Profile A

	α	β	μ
A_1 . 1	0.41	4.28 %	15.4 . 10^{-4}
A_2 . 1	0.73	9.50 %	11.1 . 10^{-4}
A_3 . 1	0.73	7.10 %	5.7 . 10^{-4}
A_4 . 1	0.67	8.85 %	3 . 10^{-4}
A_5 . 1	2.05	13.83 %	3.59 . 10^{-4}
A_6 . 1	0.35	12.60 %	93.5 . 10^{-4}
A_7 . 1	3.20	16.52 %	1.36 . 10^{-4}
A_8 . 1	1.13	8.35 %	3.60 . 10^{-4}

TABLE II

	α	β	μ
B_2 . 1	0.35	3.23 %	121. . 10^{-4}
B_3 . 1	2.22	6.88 %	14.3 . 10^{-4}
B_4 . 1	0.04	3.19 %	1784 . 10^{-4}
[illegible] 1	0.35	5.08 %	47 [illegible]

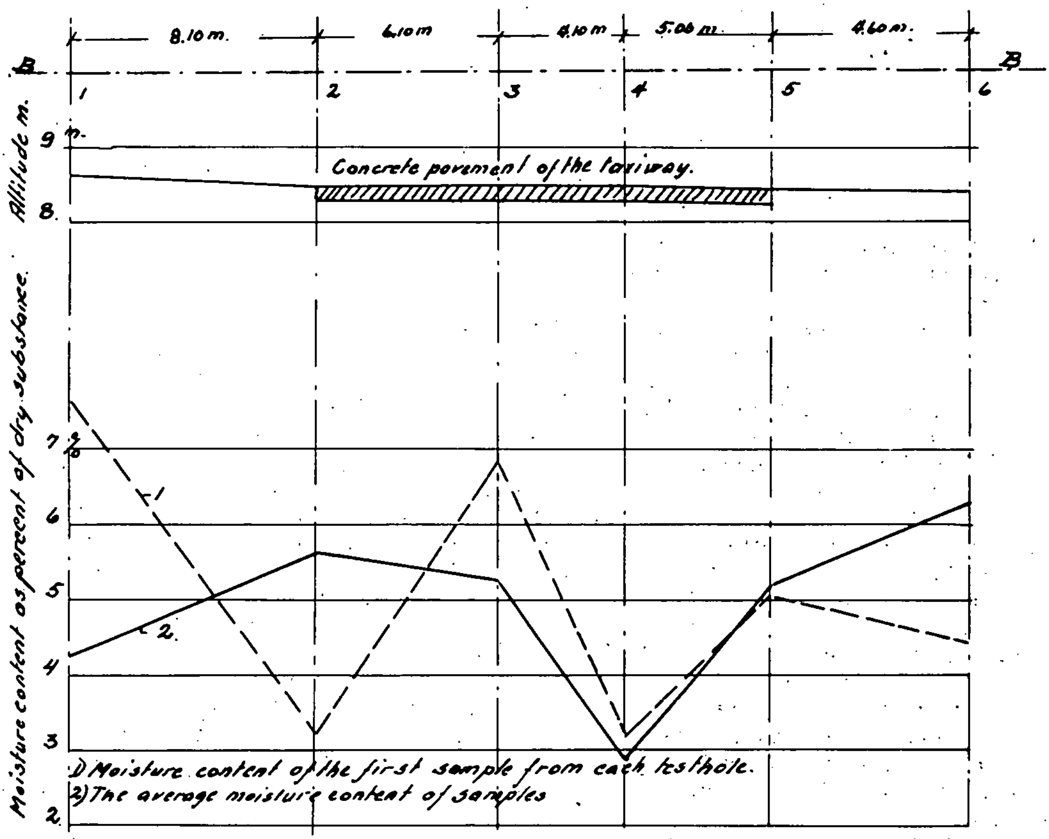

Figure 2. The figure shows the location where the test holes B_1 - B_6 were taken. The curves indicate the initial water content of the samples.

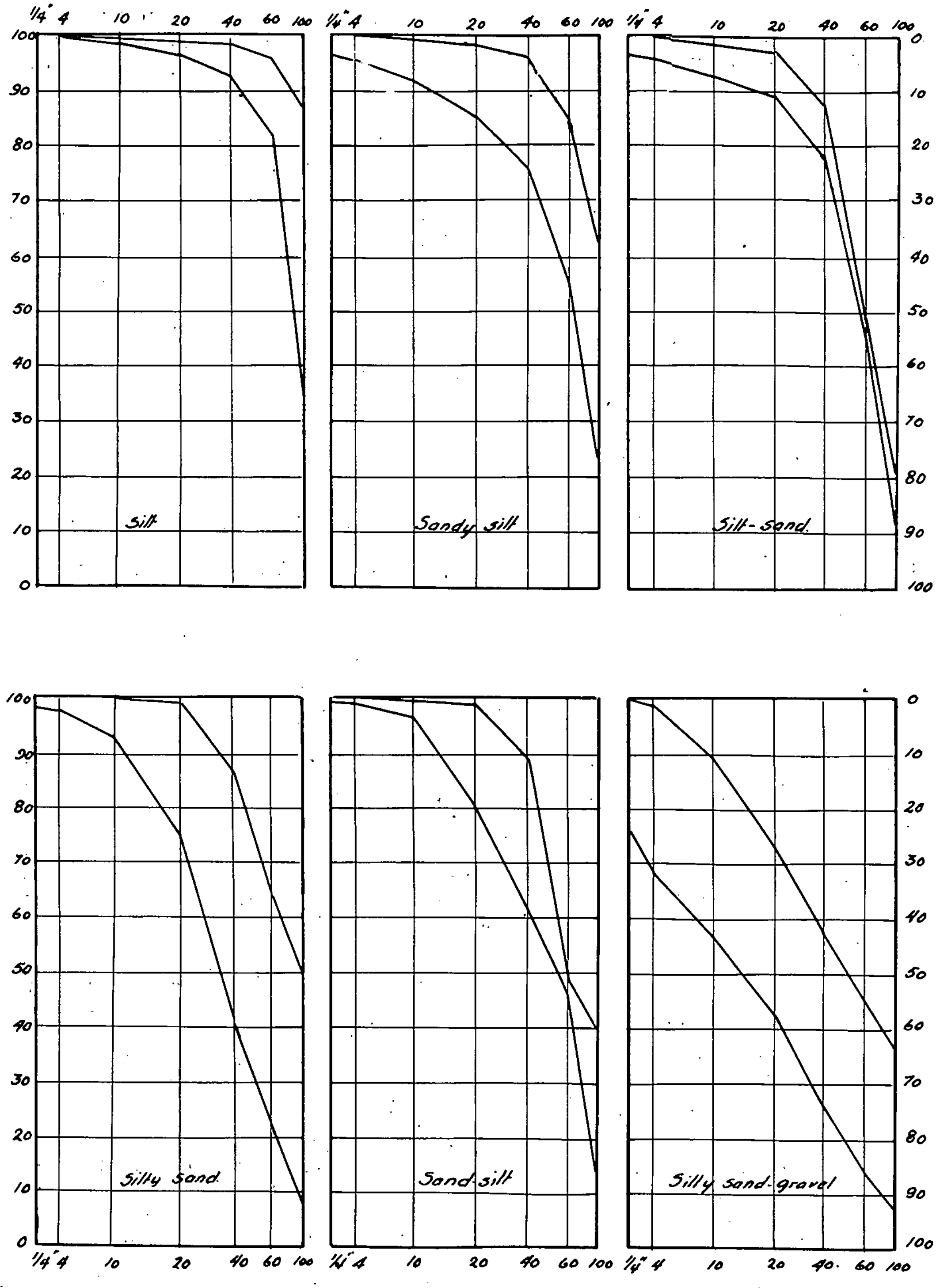

Figure 3. The figure gives the limits of the particle size for the soil classes listed in the text.

ground with subsequent total destruction of the pavement. In such cases special precautions are required. However, ice can also be formed in soils less sensitive to frost but not to the extent of causing any calamity when thawing out. In such ground special precautions are probably not taken, and an increase in the water content due to melting

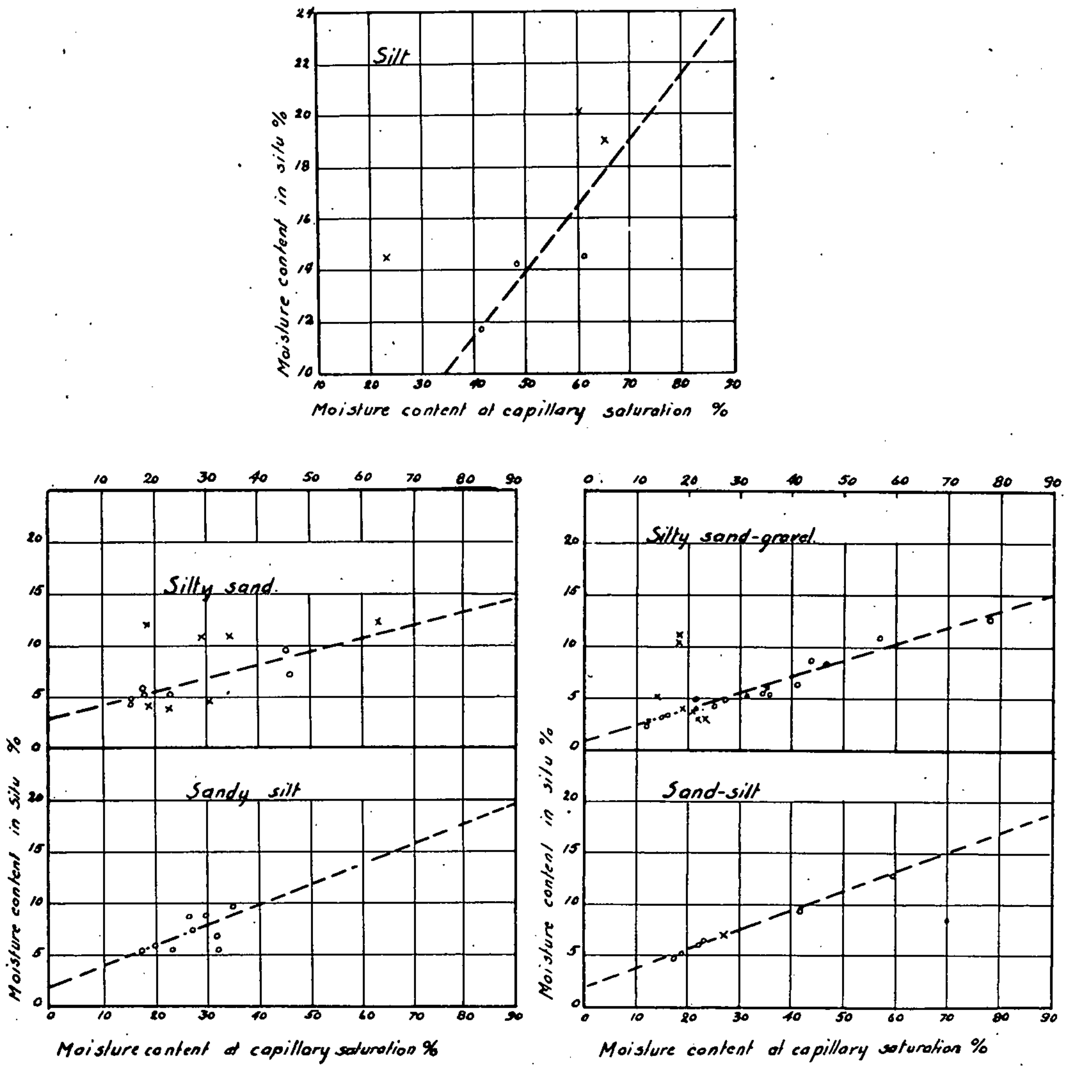

Figure 4. In the figures the ordinates represent the initial water content, the abscissas, water content by full capillary saturation. The points marked X refer to test holes located outside the pavement.

ice is to be expected. The magnitude of this increase is difficult to predict.

The physical characteristics of the soil, distance to ground water, temperature relations during freezing and thawing are here major factors. The temperature is assumed to be of particular importance during thawing. A high temperature causes rapid melting of the ice. The water will not have time to seep away and will be kneaded into the soil by traffic.

The soil of this airport is partly sensitive to frost. The border planes between strata are however so irregular that it is very probable that the capillary connection to ground water may be broken by coarse-grained strata.

The moisture analyses show no clear indications of water having been derived from melting ice. It is therefore presumed that the moisture content primarily is created by capillary action. In profile A the moisture is probably drawn from the ground water. This is considered out of the question in the case of profile B. An absorption from the sides, however, appears to have been favored by the weather conditions during the preceding 6 months. Table II shows daily precipitation and temperature at 8 a. m. from December 1, 1948 to June 2, 1949, when the samples were taken.

The total precipitation during May amounted to 96. 5 mm (3. 8 in.) of which 35. 5 mm (1. 4 in.) fell during the last 5 days of the month. There was no precipitation during June 1 and 2. Since the terrain as mentioned is level, it is presumed that the percentage of precipitation seeping into the ground would be fairly high.

The analyses determined: (1) Initial water content, (2) Permeability, (3) Water content by full capillary saturation, and (4) Granular composition. Initial moisture content is determined as percentage of oven-dried material weight.

The permeability was determined at room temperature 16 to 18 C. using undistilled water. The air-dried samples were well mixed and tamped into glass tubes of 20 mm diameter (3/4 in.) under addition of water. The permeability is derived from the following formula:

$$\mu = \frac{V \cdot 1 \cdot 10.000}{H \cdot F \cdot t}$$

μ = permeability . 10. 000
V = the quantity of water in c. c passing through a body of cross section
F = sq. cm and length 1 cm
H = the effective head in cm
t = the time in sec. it took the water-quantity V to pass through the sample.

The moisture content by full capillary saturation was determined by tamping the samples into glass tubes of 20-mm. diameter and 90 mm. long under addition of water. The tubes were left standing in about 10 mm. water for 72 hr. and the moisture content of the middle third of the tube was determined in the usual manner.

The screen analyses were made on material oven dried 5 hr. at 105 to 110 C. The following collection of sieves were used: U. S. Standard Nos. 100, 60, 40, 20, 10, 4, 1/4-in.

A few of the samples contained grains larger than 1/4-in. but in insignificant quantities.

The samples were classified as: fine sand and silt (all material passing sieve 60), sand (material passing 10 but retained on 60), gravel (material retained on 10).

With increasing grain-size the following classification has been employed: (1) silt, (2) sandy silt, (3) silt sand, (4) silty sand, (5) sand silt, (6) silty sand-gravel, and (7) sand gravel.

Figure 3 gives the limits of the particle-size distribution for the soil classes listed above.

In Figure 4 the ordinates represent the initial water content of the samples and the abscissas water content by full capillary saturation. As can be seen the points are grouped fairly closely along straight lines, i. e. , for the same soil type the ratio between initial moisture and the moisture content by full capillary saturation is farily constant.

From Figure 4 this ratio is as follows:

For silt	0. 45	
Sandy silt	0. 195	Average 0. 17
Silty sand	0. 133	
Sand Silt.	0. 189	
Silty sand gravel .	0. 161	

In fine-grained soils the voids will generally be of smaller cross section, i. e. , larger capillary forces and more water absorption. This relation is expressed by silt in above table. For the soil classes sandy silt down to silty sand-gravel the ratio is fairly constant. This indicates that the pore sizes for the different classifications in this case must be of approximately the same order.

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

Conclusion

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

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

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

DISTRIBUTION OF CAPILLARY MOISTURE AT EQUILIBRIUM IN STRATIFIED SOIL

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

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

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

$$df = -sdT + vdP - dw_m \tag{1}$$

in which

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