Summarizing, it can be said that both methods have proven themselves in laboratory and field tests and promise to become satisfactory and very useful tools for the measurement and continuous recordings of moisture content and density of soils.

Field and Laboratory Applications

The progress in research leading to improvements, refinements and special applications is rapid. In two months' time major alterations have been made to produce a greater accuracy and a reduced time of measurement. In that same period the problem of radiation hazard has been virtually eliminated by the use of the polonium-beryllium as a source rather than radium.

These improvements and experimental application to various problems has shown that the existing apparatus is suitable for locating seepage zones as they are found in landslides, dams and in drainage investigations. Special adaptations have shown that moisture control in concrete aggregates can be exercised in batching plants and the density obtained by compaction quickly determined in the course of the work.

WATER IN HIGHWAY SUBGRADES AND FOUNDATIONS

F. N. Hveem, Materials and Research Engineer, California Division of Highways

The structural integrity and endurance of almost every engineering work is jeopardized by the action of water. The permanence of relatively perishable materials, if protected from moisture, is illustrated by the ancient buildings, manuscripts, fabrics, and even cereal grains preserved for thousands of years in Egypt, which of course, is noted for the dryness of its climate. The rapid deterioration of all things in a warm, humid climate points the contrast.

In its simplest form then, one of the major problems confronting the civil engineer is the necessity for guarding against or combating the deleterious effects arising from the action of water upon the materials of construction. Everyone is aware of the more spectacular attacks of water, such as the destructive wave action along the shores of oceans and lakes and the washing out of bridge piers or damage to embankments by rivers during flood. The necessity for providing waterproof roofs and protective coatings on most buildings and structures is common knowledge. Engineers have also recognized that water has an adverse effect upon the ability of soils to serve as foundations for dams, buildings, and even pavements for highways and air fields.

A great deal has been written on the subject of bearing or supporting power of soils, and it may be significant to note that this particular field of engineering is generally classed under the heading of "soils mechanics." When a mixture of sand and gravel is mixed with a liquid such as asphalt for the purpose of producing a pavement, such mixtures are invariably referred to as bituminous mixtures or asphaltic pavements, even though the amount of asphalt present commonly does not exceed 5 or 6 percent by weight of the total mass. When considering the properties of soils or granular base materials, however, engineers rarely mention that they are dealing with a water-soil combination even though the water content commonly ranges between 5 and 30 percent of the weight of soil.

Narrowing our attention to the special problems surrounding the construction of adequate bases and foundations for pavements, we are forced to conclude that the fundamental relationships depend almost entirely upon the effects of water upon the particular soils in place. The long history of pavement failures due to foundation troubles and inadequate soil support casts no particular credit upon the engineering profession, and when such failures continue to reoccur, it is evident that there is a lack of understanding and probably insufficient knowledge of the mechanism by which water is introduced into the soil and of its effects when present. The fact that water is responsible for most of the troubles has, of course, not been entirely overlooked, because texts on highway engineering have stressed the importance of drainage, and for a great many years it has been the practice to provide drainage structures, road-

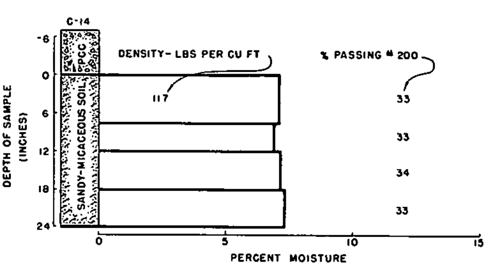

Figure 1. Shows an example of comparatively uniform moisture distribution under a pavement that had been down for 13 years at the time the samples were taken. The soil is a very uniform sand-micaceous silt and the moisture content of approximately 7 percent represents 44 percent of saturation.

side ditches, and numerous varieties of underdrains utilizing tile, perforated pipe, or trenches filled with gravel in an endeavor to drain out the objectionable water. Failures have persisted in spite of these attempts, and a few engineers have come to realize that it is often impossible to remove or reduce the moisture content by the method of simple drainage.

A few years ago, a Highway Research Board committee, headed by Dr. Hans F. Winterkorn, was formed to study the problem of non-gravitational water. However, I am not aware that this committee has ever taken any definite action on the problem. Dr. Winterkorn also wrote a paper entitled "Climate and Highways" which was presented at the June 1944 Meeting of the American Geophysical Union (Section of Meteorology). Briefly, Dr. Winterkorn directed attention to a number of facts and factors, some derived from theoretical studies and laboratory investigations and others based upon direct observation of field installations, all of which seemed to indicate that a principal source of moisture accumulation in the soil is through the condensation of vapor in the soil atmosphere. Briefly, the pores in the soil are filled with air, and presumably the air is forced in or out of these pores with every change in barometric pressure and temperature.

Other investigators have shown that most engineering materials are pervious to the passage of water in the vapor phase. This includes asphalt films of substantial thickness, most Portland cement concrete, wood, brick, etc. Certainly the more porous structure of soils offers little or no obstacle to the passage of water in the vapor phase. The bulk of literature and instruction dealing with soils for engineering purposes leaves the impression that water can enter only by two very similar means or mechanisms: by percolating downward through the soil from rainfall and melting snow and by the so-called capillary movement by which water is drawn through the pores by a sort of wick action. There is no doubt that water does move by such means. However, there is an increasing amount of evidence that water accumulates beneath pavements under conditions that seem to rule out either direct percolation or capillary action. If engineers are to devise corrective or preventive measures, it is essential that the exact mechanism and path of entrance be known. Unfortunately, there is little in the way of comprehensive data on this subject. Today, there is only a limited amount of recognition that the moisture problem is more complex than hitherto believed, and most of the data is limited to investigations of existing pavements which show varying amounts of moisture in the underlying soil. I know of no comprehensive studies intended to establish the rates at which the moisture accumulates.

A few years ago Dr. Miles S. Kersten presented a "Report of Survey of Subgrade Moisture Conditions Under Existing Pavements." This paper was published in the Proceedings of the Highway Research Board in 1944. About the same year, the Materials and Research Department of the California Division of Highways was assigned the problem of investigating the causes for failures and distress often accompanied by mud-pumping at the joints in Portland cement concrete pavements.

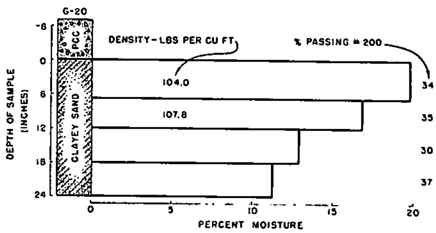

Figure 2. A number of samples were drilled where the moisture content was greatest in the upper layer, while the composition of the soil is virtually identical throughout the depth sampled. This is typical of this type of moisture distribution. This pavement had been in place for 13 years.

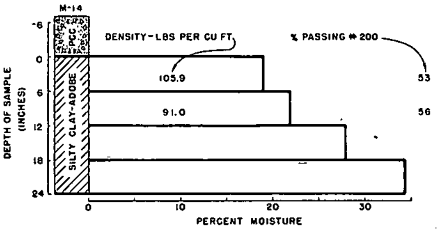

Figure 3. Illustrates the moisture distribution in reverse of Figure 2. In this case, the moisture content increases consistently with increasing depth below the surface. The soils are very heavy silty clay type containing more than 50 percent passing No. 200. The pavement was 11 years old when the samples were taken.

In seeking the causes for these difficulties, a number of pavements were selected representing all degrees of performance at the joints. Holes were cut through the pavements by means of a core drill and the underlying soil sampled in 6-in. layers to a depth of 24 in. The degree of compaction, or density in terms of weight per cu. ft., was determined at least for the first two layers encountered. Samples were taken and placed in sealed containers for determination of moisture content. The soils were tested, analyzed, and classified, using all of the methods and techniques common to an engineering soils laboratory. It may be mentioned in passing that there appears to be little if any correlation between these test results or classification schemes and the actual performance of the pavement.

For the purposes of this presentation, results were studied in order to determine whether there was any relationship or trend between the moisture content and the nature of the soil. A large number of factors were compared, such as the Atterberg limits, the Highway Research Board classification, etc., but there was little if any evidence of relationship between these values and the amount of moisture found in the soil.

The illustrations show the range of moisture distribution in the various layers.

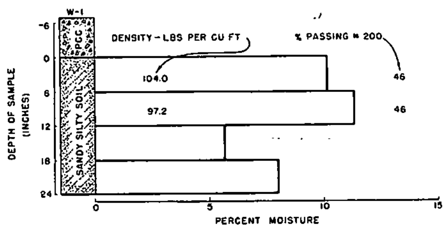

Figure 4. Represents a boring taken through the pavement into sandy, silty soil where the moisture distribution is somewhat erratic. No definite pattern evident. The pavement had been down 15 years.

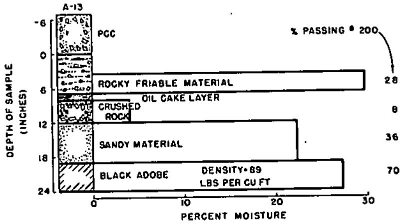

Figure 5. This figure is included to show the marked differences in the moisture content where each layer of the soil is of a different type composition. This particular boring was taken in a location where the first 6-in. layer beneath the pavement consists of a light-weight porous, granular material, presumably of volcanic tufa. The second layer represents an old road surface composed of an oil mixed surface on a crushed rock base. The third is a layer of sandy material imported as a subbase under the original bituminous surface, and the final layer is a local black adobe soil.

It is obvious that the presence or absence of moisture in the soil is a matter of primary importance to men engaged in several different professional activities. The agricultural expert or agronomist is largely concerned if the soils become too dry to support plant life. The highway engineer has reason for concern when the soils accumulate enough moisture to become lubricated and hence lose ability to support pavements subjected to heavy loading.

It is evident that the construction of tight, impervious pavements does not prevent moisture from entering and accumulating in the soil beneath the pavement. It is evident that the construction of asphaltic membranes or the presence of an old pavement beneath a layer of gravel or soil does not prevent the intermediate layer from becoming saturated. A layer of soil placed as a "sandwich" between two layer of relatively impervious pavement usually accumulates more moisture and reaches a higher degree of saturation than if placed directly on the ground. The assumption that water enters the soil by soaking downward from the surface or by capillary action from below seems to be inadequate to explain the amount of moisture that has been found beneath pavements in a great many cases. This leaves as a remaining possibility the movement of moisture in the vapor phase through the pores of the soil and the condensation of vapor, due to either changes in temperature or in pressure. It has been pointed out that soils will hold more moisture by adsorption when temperatures are low and will yield up this adsorbed moisture in the form of free water when temperatures rise. Direct observation of roadway performance seems to lend ample support to this theoretical concept. So far as California experience is concerned, we lack convincing or direct proof to establish the path by which moisture enters the subgrade soil.

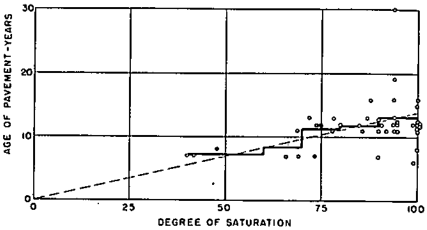

Figure 6. This chart illustrates the degree of saturation compared to the age of the pavement. These points seem to indicate that the rate at which moisture accumulates may be quite slow. While the data are far from being conclusive because all pavement samples were at least 5 years old when samples were taken, it is undoubtedly true that in some cases interlying soils may have been saturated at the time of construction. Nevertheless, there appears to be a trend indicating that it may require a period of more than 10 years for complete saturation to develop.

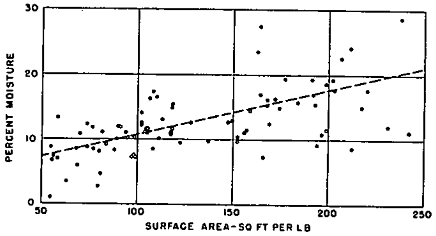

Figure 7. Illustrates the relationship between the calculated surface area of the soil particles and the amount of moisture. This relationship apparently represents the only discernible trend between characteristics of the soil and the moisture present. While the relationships indicated are not sharp or precise, it is also true that the values shown for surface area equivalents are only rough approximations and may be considerably in error for the finely divided clays or soils containing an appreciable amount of colloidal sizes. The indication that there is some relationship between particle surface area and the moisture content may lend support to the theory that moisture accumulates largely as a result of condensation from water vapor.

Admitting that moisture can enter through porous pavements or leaky surfaces, and recognizing that moisture can migrate upward by capillary action to produce saturation when the water-table is near the surface, there remains the strong probability that moisture also accumulates as a result of water vapor moving freely through the pores in the soil and condensing upon the soil particles when subjected to a drop in temperature.

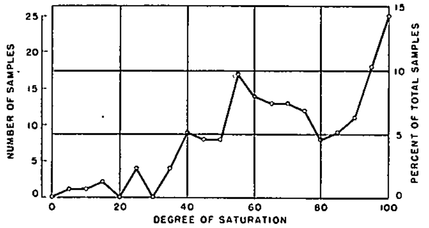

Figure 8. This chart shows the relative number of samples representing the various degrees of saturation. While the average of all samples taken corresponds to a moisture content of approximately 79 percent saturation, it is evident that a relatively high percentage have approached or reached saturation.

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