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# SOME CAPILLARY PHENOMENA IN SANDY MATERIALS

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## SYNOPSIS

The study of the physical principles on which the accumulation of moisture under pavements is based is an engineering problem of major importance This paper should be considered as an attempt to disclose some of these principles from a few laboratory tests on sandy materials (Ottawa sand and two California sands) Emphasis is laid on the items not sufficiently clarified in the highway and runway literature such as. (a) horizontal capillarity, as in the case of movement of moisture from the edges of a pavement toward its center, and (b) the boundary effect when the moving moisture reaches an outflow face or some obstacle handicapping its further movement. Some consideration is also given to the phenomenon of condensation of water vapor

Variation in moisture content of the base and subgrade of a pavement is a subject matter worthy of detailed study. Considerable factual material collected by highway and runway engineers, most of which has been published in the *Proceedings* of the annual meetings of the Highway Research Board of the past ten years (*1*, *2*),[1] shows that the moisture content of a subgrade built at an optimum moisture content may become appreciably different some time later. Some cases of destruction of pavements due to accumulation of moisture under the pavements, even in desert regions, have been reported (*3*)

Assuming that water does not penetrate through a pavement, the sources from which additional moisture may come to a subgrade (or the sink toward which it moves from the subgrade) are (a) the water table, and (b) the edges of the pavement In both cases, capillarity is a predominant factor, though some horizontal movement from the edges of a pavement under the action of a hydraulic head, however small, also should be considered. Again, capillarity has to be studied in conjunction with its sister phenomenon, condensation of water vapor, since capillary moisture moves in both liquid and gaseous phases, and a source of moisture at the edges of a pavement from a saturated atmosphere is quite a possibility

If a program of the study of accumulation of moisture under pavement should be prepared, the beforementioned items such as capillarity, both vertical and horizontal, and condensation should be included in it. The obscure phenomenon of splitting of the capillary moisture into a fluid phase and a gaseous phase and the estimation of the quantity of the latter, are worthy of consideration. Finally, the provenance (or location of the original sources of supply) of water or water vapor that causes increase of the moisture content

[1] Italicized figures in parentheses refer to list of references at the end of this paper

under a pavement, should be sufficiently clarified.

In this paper, a few tests on capillarity in three sandy materials are described. The whole work was of a short duration and is preliminary in character.

EQUIPMENT USED

The tests were vertical and horizontal capillarity tests (V- and H- tests) performed in glass tubes, $1\frac{1}{4}$ in. in diameter, the length of the tubes being 20, 30, and 40 cm., respectively. Symbol L with the corresponding number (for instance, L-40) is used hereafter for designating the length of an experimental tube. As shown in Figure 1 (a) and (b) each tube was provided with a brass cap at that end touching the free water level or saturated felt, respectively (termed "origin of flow" hereafter), and with a vent for eliminating air from the sample at the opposite end.

In a V- test a tube filled with experimental material was placed on a cushion of saturated felt, the free water level being maintained flush with the top of that cushion, as described elsewhere (*3a*). Most of the horizontal tests were felt-wrapped tests (symbol HW or simply H). Felt used in these tests was common white felt, $\frac{1}{4}$ in. thick. The cap of the tube was tightly wrapped in felt, with a felt disk against the end of the tube (Figs. 3 and 4). Water was brought to the felt by syphon capillarity (Fig. 3); in actual tests the felt strip shown overhanging from the beaker in Figure 3 touched the wrapping of the tube to produce a continuous capillary flow. This felt arrangement was used to decrease the non-uniform moisture distribution in a cross-section of a tube and to eliminate the necessity of rotating the tube about its longitudinal axis during the experiment. As it may be seen from Figure 3, the wetted line in the sand was practically normal to the longitudinal axis of the tube, without the necessity of rotating the tube. Still another test was the well-known submerged capillarity test in a box (Fig. 2). The symbol used for this test is HU.

The moisture distribution along the longitudinal axis of the tube was determined occasionally; but during each test the tube was rapidly weighed several times to determine the total weight of moisture contained in it at a given time-moment, (presumably in both liquid and gaseous state). In addition, the position of the center of gravity of the moisture contained in the tube at a given time-moment was determined. This was done by

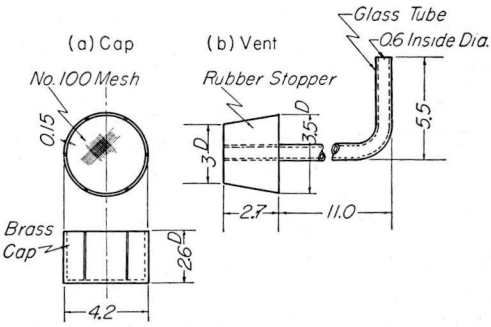


**Figure 1. Cap and Vent of a Tube (metric measures)**

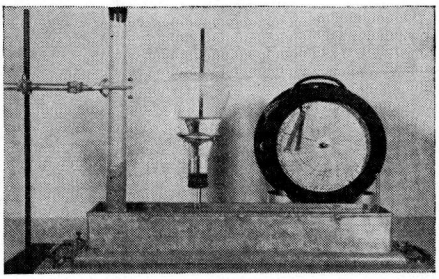

**Figure 2. Experimental Box for Vertical (V) and Horizontal (HU) Capillarity**

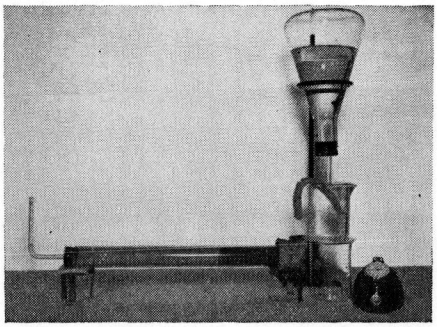

**Figure 3. Horizontal (HW) Capillarity**

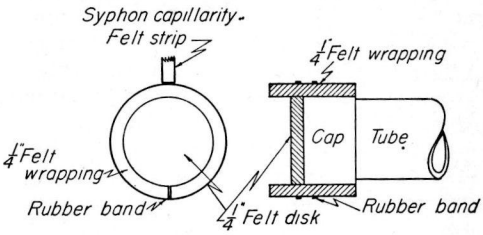


**Figure 4. Arrangement of Felt for Horizontal Capillarity Test**

using a simple device shown in Figures 5 and 6 The tube, filled or empty, was placed on the wooden platform (A, Fig 6) and gently pushed (from right to left in Fig. 5) until it started to tip Wooden blocks B served to hold the tube in position along the axis of the platform A. The distance $l$ from the center of gravity of the tube to the origin of flow (tip of the tube) was then simply read on a

**Figure 5. Wooden Device for Determining the Position of the Center of Gravity of a Tube, Empty or Filled**

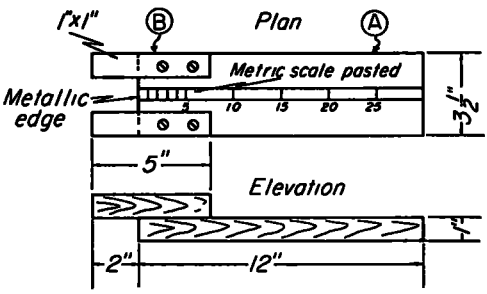


**Figure 6. Wooden Device for Determining the Position of the Center of Gravity of a Tube, Empty or Filled**

scale pasted on the platform Let $W_1$ and $W_2$ equal the weight of the tube (1) filled with dry soil powder, and (2) when there is some moisture in the tube arbitrarily distributed. Also, let $l_1$ and $l_2$ equal the corresponding values of the distance $l$ from the center of gravity of the tube to the origin of flow. Designating with $x$, the distance from the center of gravity of the moisture to the origin of flow, and considering the tube filled with soil and moisture just at the time-moment when it is about to tip (state of limit equilibrium), there can be written:

$$W_2 l_2 - W_1 l_1 - (W_2 - W_1) \cdot x = 0 \quad (1)$$

from which

$$x = \frac{W_2 l_2 - W_1 l_1}{W_2 - W_1} \quad (2)$$

*Example* —The tube filled with dry material weighed $W_1 = 892\ 1$ g and its center of gravity was $l_1 = 19\ 75$ cm distant from the origin of flow plane After some capillary moisture entered the tube, these values were $W_2 = 940\ 2$ g. and $l_2 = 19\ 20$ cm. Using Equation (2) it may be found that the center of gravity of the moisture was 9 4 cm distant from the origin of flow

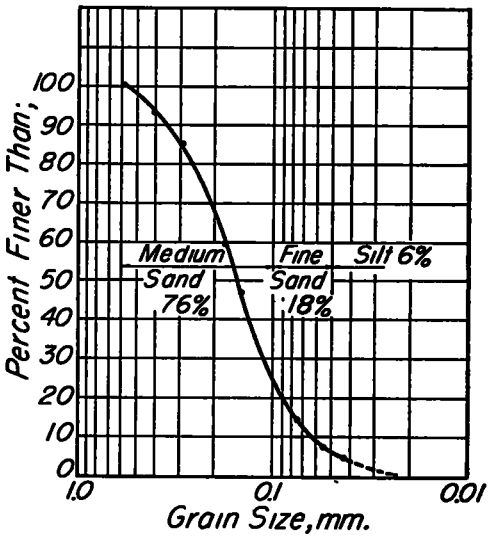


**Figure 7. Size Distribution Curve of Antioch, California, Silty Sand**

MATERIALS USED

Three materials, all non-plastic, were used in these tests They were.

(a) Fine Ottawa sand, from which 98 percent was retained on sieve No 100 (149 micron openings); 72 percent on sieve No 50 (297 micron openings); and 2 percent on sieve No 30 (590 micron openings)

(b) Medium to fine silty sand from Antioch, California, located in the San Joaquin River valley. The size distribution curve of this material is shown in Figure 7.

(c) Kings River sand, from Avocado pit, Fresno County, California, portion totally passing sieve No. 200 (74 micron openings).

Thus, the material labeled (b), i.e., the Antioch sand, is between the materials (a) and (c), insofar as the size of grains is concerned. The values of the coefficients of permeability for these materials have not been determined; but quantitative permeability tests have shown that the values of the coefficient of permeability for material (a) is the highest, and that of material (c) is the lowest of the three materials in question.

### SAND-PLACEMENT PROCEDURE

The tube was held in an approximately horizontal position, and a portion of dry soil powder introduced in it, using a spatula, also horizontally held. Thereupon the tube was brought to a vertical position and the level of the material evened by gently knocking the tube against a one-layer felt cushion placed on a table. After the tube was filled in this way by small portions practically to the top, leaving space only for the vent (Fig. 1 b), 50 blows on the flow table (as used in concrete testing, height of fall ½ in. per blow) were given to it, again using a one-layer felt cushion. In most cases, no addition of material was needed after the flow-table compacting. The tube was then weighed, and the position of its center of gravity determined.

### CAPILLARITY OF OTTAWA SAND

The V- test in 20-, 30-, and 40-cm. long tubes has shown that in all cases the weight of moisture lifted very quickly was the same (18.5 g.), the height of capillary rise being about 6.5 cm. The next day, after a cool night, the amount of moisture lifted from the water table increased considerably (to 24.7 g. and even to 27.2 g.), with spotty moisture distribution (Fig. 2). An increase in the total moisture content in the tube after the wetted line reached the top of the soil column was observed in all cases when this phenomenon was investigated. Apparently in this particular case, the decrease of temperature contributed to the increase of the weight of the total moisture lifted, because of condensation.

The horizontal movement of moisture in the Ottawa sand apparently is a combined action of capillarity and hydraulic head. When the origin of flow is put in contact with the outside water, the horizontal pull is too weak to make all the moisture move horizontally in a capillary way. A part of the moisture just falls down and starts moving under the action of the hydraulic head, and such a motion may be of indefinitely long duration. Simultaneously, with the horizontal motion under head (depicted by letter A in Fig. 8) and after its completion, moisture moves up by capillarity (arrows B, Fig. 8) until the whole tube is completely filled, except, perhaps, a bubble of entrapped air at the middle (C in Fig 8) In a typical L-40 test, water reached the other end of the tube (total length of movement 39.1 cm.) in 76 min., and moved 95 1 g. of moisture, which afterwards increased to 103.7 g. The temperature during this particular test was 71 F.; the voids ratio of the material being about 0 50.

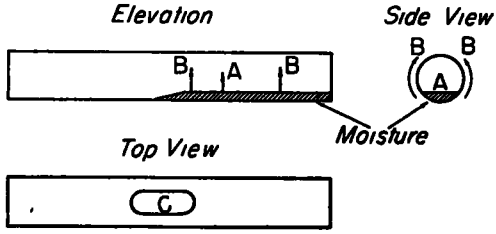


**Figure 8. Schematic Representation of Horizontal Capillary Movement in Coarse Sand**

### CAPILLARITY OF THE ANTIOCH SILTY SAND

Figure 9 refers to two tests made in a constant temperature room (temperature 70 F., relative humidity 50 percent). In this and the following figures three values are designated with letters $W_0$; $M_0$; and $CG_0$. Symbol $M_0$ stands for the weight of moisture moved (in grams); symbol $CG_0$ stands for the distance of the center of gravity of the moisture moved from the origin of flow plane (in cm.); and $W_0$ stands for the product of the two preceding values (in cm.-gr.). In the case of a V- test, this product is that part of the total work done on the moisture corresponding to the work against gravity. The subscript "zero" on the symbols $W_0$, $M_0$, and $CG_0$ indicates that the tests were run at a constant temperature of 70 F. The absence of the subscript "zero" on the symbols above mentioned shows that the tests were performed at a variable temperature.

A V- test and an H- test were made under approximately equal conditions of packing (voids ratios 0.68 and 0.66, respectively) and length of soil column, the end of which was

reached (39.5 cm and 38.0 cm. respectively). The total weight of moisture moved was approximately the same in both cases (86.6 g. in the V- test, and 92 1 g. in the H- test), but the time required to perform this duty was approximately double in the case of the V- test. It should be noticed that this ratio of the times gradually increases during the test, as may be seen from the curves, Figure 9.

No graphs are presented in this paper for the following simultaneous tests on Antioch sand made at a variable temperature rising from 67 F at the beginning of the test to 71 F at its end. The experimental data presented hereafter refer to an V- test and an H- test, respectively. The total length of capillary movement was 38.0 cm. and 38.7 cm. The time required to reach the top of these columns was 251 min and 150 min. The total weight of moisture moved was 94.8 g. and 99 3 g. The voids ratios were 0 61 and 0 64. In other words, the material was packed tighter than in the two tests on Antioch sand shown in Figure 9. Since the average temperature of these tests was close to that of the constant-temperature room (70 F.), it should be concluded that the increase in the volume of the moisture moved and a rather short duration of the test as compared with Figure 9 are due to tighter packing of the experimental material.

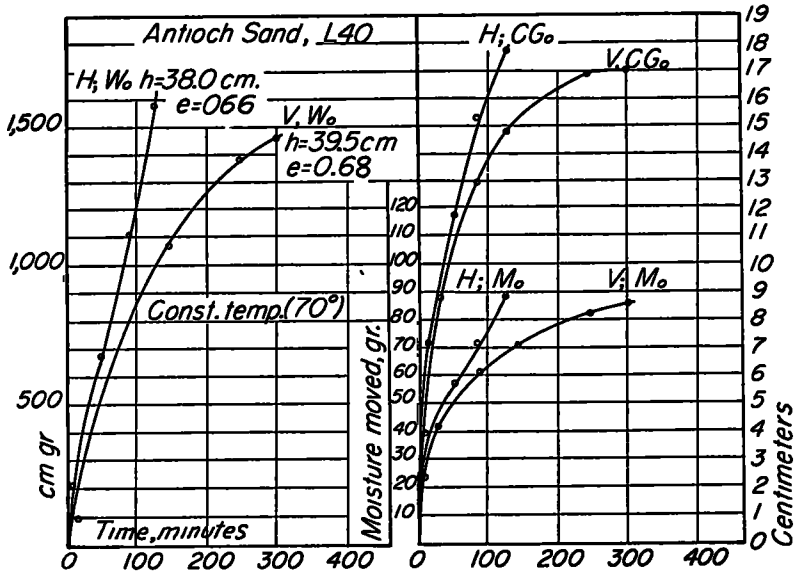


**Figure 9. Vertical and Horizontal Capillarity Compared (Antioch Sand)**

CAPILLARITY OF THE KINGS RIVER SAND

Figure 10 shows the influence of packing. Two horizontal tests (L-30) were made under equal conditions except packing (voids ratios 0 80 and 0.60, respectively). The total volume of moisture was larger in the case of loose packing (84.6 g against 65.7 g ). Apparently this could be explained by the concentration of moisture in the neighborhood of the origin of flow (see curve $CG_0$, Fig. 10) The total duration of the test was shorter in the case of tight packing (573 min against 738 min.)

In general, in many cases, capillary movement in fine KR sand was practically identical in both vertical and horizontal directions. Just at the beginning of this series of tests, three simultaneous tests (a V- test; an HU-test, and an HW- test) were made at a variable temperature Figure 11 shows the experimental results obtained; the only more or less serious difference was in the position of the wetted line which was slightly higher in the V- test than in the other tests. The difference between vertical and horizontal motion in subsequent tests was more pronounced but still insignificant, and in no way comparable to the analogous difference in the case of Antioch sand (Fig 9).

Figure 12 has been prepared for comparison of vertical and horizontal capillarity combined with loose packing in the H- test (voids

ratio 0.80 against 0.62 in the V- test). The volume of moisture moved was somehwat larger in the case of the H- test (84.6 g. against 80 g. in the V- test); and again loose packing in the H- test contributed to the low position of the center of gravity of moving moisture as it also did in Figure 10.

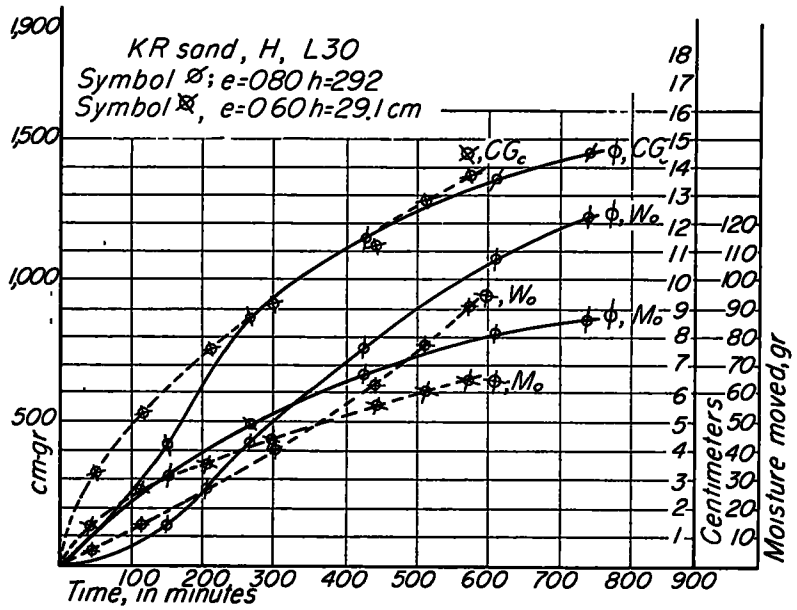


**Figure 10. Comparison of Tight and Loose Packing (Kings River Sand)**

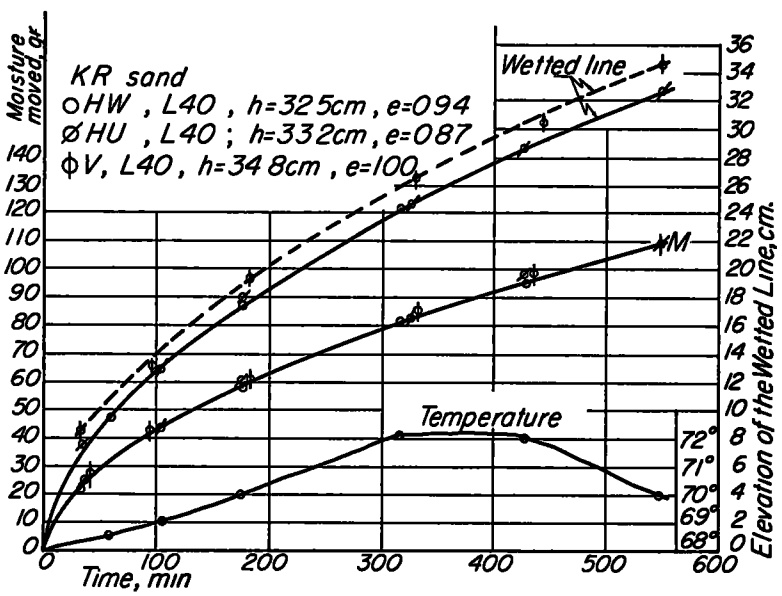


**Figure 11. Three Simultaneous Capillary Tests on Kings River Sand**

Figure 13 shows the effect of the high temperature on horizontal capillarity. In both tests shown in that figure, the packing was

rather loose, and the low position of the center of gravity of the moving moisture at the beginning of the test appears in either case. The weight of moisture moved under conditions of high temperature at the end of 5 hr. was but slightly higher than at 70 F. temperature (55.8 g. against 53.7 g.). It is true also that the material subjected to the action of a high temperature was tightly packed, and this circumstance apparently compensated for a part of the effect of high temperature.

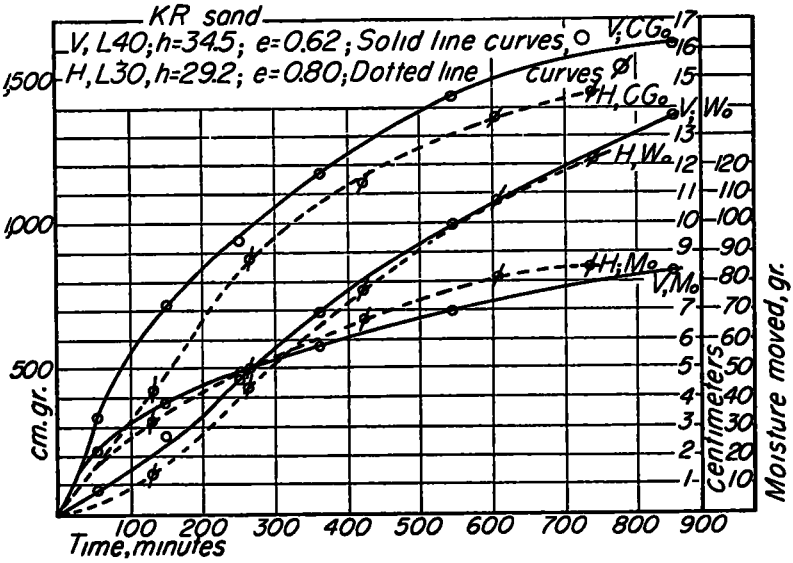


**Figure 12. Vertical and Horizontal Capillarity Compared (Kings River Sand)**

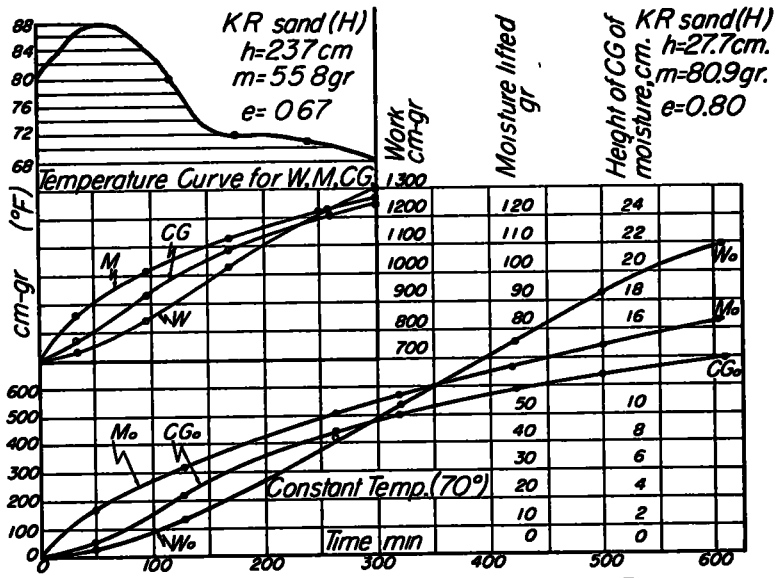


**Figure 13. Horizontal Capillarity at Constant and Variable Temperature**

CENTER OF GRAVITY OF CAPILLARY MOISTURE

According to the work by Leverett (*4*) and originally by Buckingham (*5*) a more or less uniform distribution of the capillary moisture through the length of the experimental tube

was expected, since that length was only 40 cm. or less. This means that the center of gravity of the moving moisture should have been located somewhere about the middle of the wetted soil column. In reality this was so (Fig. 14), and the center of gravity of the moving moisture was only slightly lower than 0.50 of the height of the wetted soil column. Two exceptions are to be mentioned: (a) in some (but not all) V- tests this ratio was slightly over 0.50 (Fig. 14, upper $CG_e$ curve); (b) in the case of loose packing in a H- test the center of gravity was low (Fig. 14, lower $CG_e$ curve) as previously mentioned (at least so far as KR sand is concerned).

### DEGREE OF SATURATION

The degree of saturation was computed for all tests as the ratio of the total weight of

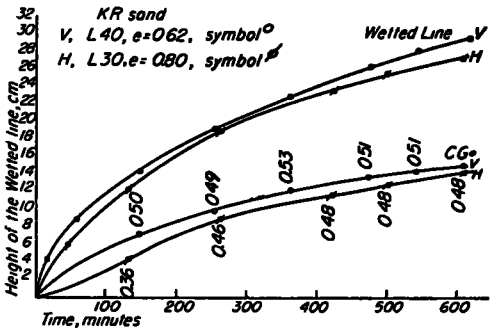


**Figure 14. Position of the Center of Gravity of Moisture with Respect to the Wetted Line**

moisture in the tube at the time-moment when the wetted line reached the top of the soil column (or other predetermined elevation) to the maximum possible total weight of moisture that can be accommodated in the pores of the wetted column In no case was the degree of saturation 100 percent, but it was very close to that figure in H- tests on Ottawa sand (L-40). In V- tests (L-40) on Ottawa sand, the degree of saturation was insignificant as may be concluded from the experimental results described in the Section on Capillarity of Ottawa Sand.

The degree of saturation in both vertical and horizontal tests on KR sand (L-40) was close to 83 percent as an average. This figure held also for horizontal tests on Antioch sand (L-40). The average degree of saturation for V- tests on Antioch sands (L-40) was about 77 percent, however.

### CONDENSATION PHENOMENA

Condensation was observed in several cases of both V- tests and H- tests, generally in the form of drops, sometimes large, sometimes microscopic, on the inner wall of the experimental tube. As a rule, condensation was caused by the dropping of the ambient air temperature. On one occasion fine, silvery condensation was observed in a H- test in the constant temperature (70 F.) room. Since no records of actual temperature or barometric pressure were available for the room at that time, this case remained unexplained.

It should be noticed that in all observed cases of condensation (L-40), there was no condensation either next to the origin of flow plane or immediately below the wetted line. A typical case of condensation is shown in Figure 15.

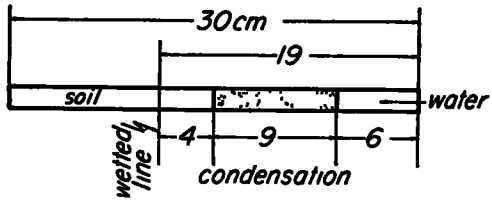


**Figure 15. Condensation in the Experimental Tube (an Example)**

### THE BOUNDARY EFFECT

After the wetted line had reached the top of the soil column, the volume of moisture in the tube increased to reach a maximum, then dropped down, and afterwards fluctuated about a certain average. Apparently on reaching the top of the soil column, the moving moisture does not satisfy conditions of equilibrium and has to return back (boundary case). Apparently a part of the capillary moisture in the tube is returned to the source through the tip of the tube, the "origin of flow".

Two V- tests (L-40) of long duration were performed, one on KR sand (voids ratio 0.62) and the other on Antioch sand (voids ratio 0 64). The fluctuations of the total volume of moisture contained in the test tube and of the position of its center of gravity are shown in Figure 16. The expression "end of rise" used in this figure corresponds to the time-moment when the wetted line reached the top of the soil column.

The values of the degree of saturation are given in Table 1.

"Average saturation" corresponded to the average around which the weight of the moisture fluctuated in its tendency to reach the position of equilibrium (98 5 g. for KR sand and 90 g for Antioch sand, Fig. 16).

temperature room did not permit this elimination of factors, as may be seen from the temperature curve of Figure 16. Checking and further research along these lines is planned.

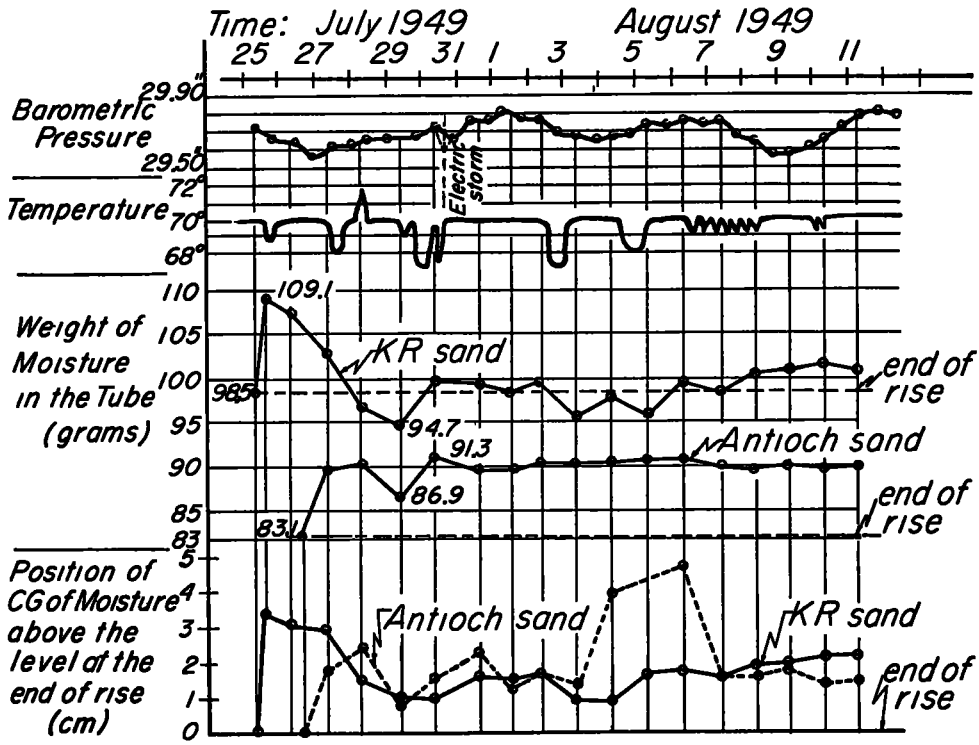


**Figure 16. Boundary Effect**

TABLE 1
DEGREE OF SATURATION

| | KR Sand | Antioch Sand |
|---|---|---|
| | % | % |
| (a) At the end of rise | 86 | 71 |
| (b) At the maximum saturation | 95 | 81 |
| (c) At the minimum saturation | 83 | 74 |
| (d) At the average saturation | 86 | 76 |

The diagram at the bottom of Figure 16 shows the shifts of the center of gravity of the capillary moisture in the tests under consideration. The original aim of these tests was to make them at a constant temperature (70 F.) and a constant humidity (50 percent), and to study the possible effect of atmospheric pressure on capillarity. However, certain irregularities of these conditions in the constant

DISCUSSION

As a measure of capillary pull for a given soil under variable circumstances, the quantity of water moved by the soil has been chosen. The circumstances in question are:

(a) vertical motion as compared with horizontal
(b) tight packing (i e , a smaller voids ratio) as compared with loose packing (i e , a larger voids ratio) and
(c) low temperature of the test as compared with a higher one

Table 2 prepared from Figure 9 shows that under equal conditions of packing and temperature the only difference between the vertical and the horizontal motion in Antioch sand consisted practically in the speed of motion since the position of the center of gravity of a

given quantity of capillary water was practically at the same distance from the origin of flow in both cases.

Table 3 prepared for horizontal motion of capillary moisture in KR sand on the basis of the results in Figure 10 shows the influence of packing Tight packing decreased the speed of capillary motion, and moisture that moved forward was more uniformly distributed along the length of the test tube than in loose sand. In the latter case, the center of gravity of the moving fluid was closer to the origin of flow than in the case of tight packing

Table 4 prepared for horizontal motion of capillary moisture in KR sand on the basis of Figure 13 results shows the influence of temperature. In this case, the warm capillary stream was pulled forward quicker than the cold one and the center of gravity of the cold capillary stream was closer to the origin of flow than that of the warm one

TABLE 2

| Quantity of Water Moved | Time of Motion | | Distance of the C G from Origin of Flow | |
|---|---|---|---|---|
| | V | H | V | H |
| g | min | min | cm | cm |
| 80 | 220 | 107 | 16 6 | 16 5 |
| 70 | 135 | 82 | 15 0 | 15 0 |
| 60 | 80 | 60 | 13 0 | 12 8 |
| 50 | 48 | 35 | 10 2 | 9 8 |
| 40 | 22 | 15 | 7 8 | 7 6 |

The writer believes that study of the influence of temperature on the capillary flow does not merit attention since under the field conditions the temperature is never equable. This is the reason why the influence of temperature has been excluded from the conclusions of this paper.

From a simple inspection of Tables 2, 3, and 4, it is obvious that the speed of capillary motion in Antioch sand was several times the speed in the KR sand. This was due to the larger pore size and the higher permeability of the Antioch sand Values of these two materials were approximately the same as to porosity (about 39.0 percent for Antioch sand from an average of 7 tests and about 39 5 percent for KR sand from 5 tests). Perhaps the speed of motion was the major difference in the capillary behavior of these two materials The degree of saturation for horizontal capillarity was approximately the same in both cases. The experimental data available do not permit establishing some sharp difference in the position of the center of gravity of the moving moisture, however

Of considerable significance are the results of the tests on Ottawa sand. These tests have shown that horizontal motion of moisture in a subgrade from the shoulders to the center is due partly to capillarity and partly to the action of a hydraulic head. It is true that the latter action was clearly seen only in the case of coarse Ottawa sand. At the origin of flow at the shoulders, however, there is always an insignificant hydraulic head; and any pressure gradient, however small, will cause fluid to move through a porous medium. In studying the problem of accumulation of moisture under pavements, due attention should be paid to both vertical and horizontal capillarity acting in conjunction with condensation. However, experiments made by highway and runway engineers in the past have referred only to vertical capillarity, and it is important to complete the available information by data on horizontal capillarity, or more accurately, on horizontal motion of moisture from the shoulders of a pavement toward its center.

TABLE 3

| Quantity of water moved | Time of Motion | | Distance of C G from Origin of Flow | |
|---|---|---|---|---|
| | Tight Packing | Loose Packing | Tight Packing | Loose Packing |
| g | min | min | cm. | cm |
| 65 | 573 | 403 | 13 8 | 11 3 |
| 60 | 491 | 358 | 12 3 | 10 6 |
| 50 | 360 | 267 | 10 5 | 8 8 |
| 40 | 250 | 198 | 8 5 | 6 3 |
| 30 | 150 | 140 | 6 2 | 4 0 |

TABLE 4

| Quantity of water moved | Time of Motion | | Distance of C G from Origin of Flow | |
|---|---|---|---|---|
| | Low Temperature | High Temperature | Low Temperature | High Temperature |
| g | min | min | cm | cm |
| 50 | 267 | 215 | 8 8 | 9 3 |
| 40 | 198 | 152 | 6 3 | 7 2 |
| 30 | 140 | 88 | 4 0 | 4 0 |

Facts described in the Section on the Boundary Effect call attention to the "boundary effect", or the behavior of the fluid as it flows

past a discontinuity on the capillary properties of the porous medium (*4*). In this paper the behavior of capillary moisture as it reaches the outflow face of a sand column in a vertical test tube is described. Perhaps in actual practice, the boundary effect on vertical capillarity is more important than on horizontal capillarity since in the latter case there is generally no outflow face

## CONCLUSIONS

Conclusions of this paper are valid only for materials and tests described. Since there is a considerable difference between a test tube and the field reality, any generalization of these conclusions should be done with utmost care.

Preliminary conclusions drawn from the tests described in this paper are as follows:

1. The difference between vertical and horizontal capillarity (all other conditions such as packing and temperature being equal) consists mostly in the speed of movement, and much less, if at all, in the quantity of moisture moved or its distribution along the tube.

2. Factors contributing to quick motion of capillary moisture in a test tube are loose packing and horizontal position of the test tube. Oblique capillarity has not been investigated.

3. Loose packing of the material contributes to the concentration of the moisture in the proximity of the origin of flow.

4. Horizontal motion of moisture in a test tube apparently is due to both the capillary pull and the action of a hydraulic head. Hence, horizontal moisture movement may cover very large distances provided there is a permanent supply of moisture under head, however small, at the origin of flow.

5. The boundary effect observed in vertical capillary tests consisted in a temporary increase of the total moisture content in the tube after the upper outflow face was reached with subsequent decrease and further fluctuations around a certain position of equilibrium.

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