the earth until the filter is reached, when the flow drops vertically. This horizontal seepage creates a horizontal force through the earth and against the wall.

In closing, the writer wishes to express his admiration for the work of Mr. Homer R. Turner, Associate Roadway Maintenance Engineer in charge of drainage for his bureau. Through his vigor and intelligence, Connecticut's modern underdrain practice was successfully launched five years ago and he has continued this excellent work, with the desire to improve designs and methods from experience in the field and research in field and laboratory.

REFERENCES

1. Flint, R. F., "Glacial Geology of Connecticut," Bulletin No. 47, Conn. State Geological and Natural History Survey. 1930.
2. McClelland, T. B., "Large-scale Model Studies of Highway Subdrainage," *Proceedings*, Highway Research Board, Vol. 23. 1943.
3. "Investigation of Filter Requirements for Underdrains," U. S. Waterways Experiment Station, Vicksburg, Miss., Technical Memorandum No. 183-1, Nov. 1, 1941.
4. Adams, M. J., "Control of Underground Water," *Public Works*, Nov. and Dec. 1941.
5. Turner, H. R., "Outmoded Rural Highways Modernized by Drainage," *Public Works*, May 1941.
6. Ibid, *Proceedings*, Assn. of Highway Officials of the North Atlantic States, 17th Annual Conference, Feb. 1941.
7. Russell, M. B. and Spangler, M. G., "The Energy Concept of Soil Moisture and Mechanics of Unsaturated Flow," *Proceedings*, Highway Research Board, Vol. 21. 1941.
8. Muir, Levi, "Present Practice in the Drainage of Highways," *Proceedings*, Highway Research Board, Vol. 22. 1942.
9. Keene, Philip, discussion of above paper.
10. "Filter Design," Soils and Paving Laboratory, U. S. Engineer Office, Providence, R. I. Nov. 11, 1942.

CAPILLARITY IN SANDS

By Raul Valle-Rodas, *Bolivia, South America*

SYNOPSIS

A summary is given of the findings made during an experimental comparison of active and passive capillarity in sands. The investigation was performed by the author in the Soil Mechanics Laboratory of Princeton University in partial fulfillment of the requirements for the degree of Civil Engineer.

Tests were made with a sand separated by sieving into seven groups of different uniform size. The heights of active capillary rise observed in open tubes are compared graphically to the heights of passive capillary rise determined by means of the negative head capillarimeter as well as to the theoretical values computed by means of conventional formulas. The causes for the appreciable differences in the results as well as their trends are analyzed.

The observed non-uniform distribution of capillary water along the height of active capillary rise is recorded. The observed changes with time in the rate of active capillary rise are indicated. The observed decrease with time of the water content along the height of passive capillary rise and its distribution after flooding and drainage of the test specimens is also presented graphically. The effect of varying admixtures of finer sand particles on the observed height of passive capillary rise is reported.

The importance of the different problems encountered in highway construction and earth structures in general, which are due to the presence of capillary water in soils, prompted us to study the factors affecting capillary phenomena. Although the scope of the experimental work reported in this paper was limited to sands only, the results obtained may be of some interest for further investigations on other soils.

Capillarity in soils is commonly determined by measuring the so-called "passive" height of capillary rise. The limitations of the methods used in such determinations, however, are not well known, and they should be established for better understanding of capillary phenomena in soils. The primary purpose of the study was, to find the relationship existing between the active and passive capillarity in in sands.

METHODS OF DETERMINING HEIGHT OF CAPILLARY

Rise. The oldest and best known method of measuring capillary rise in soils is the so-called "open-tube method," in which the soil is placed in a glass tube with a screen on one end, the other end being open to the air; the first end is then placed in contact with water and the height of capillary rise (*active capillarity*) is measured from the free water surface up to the point reached by the capillary water. This method, although it is very simple and reproduces more exactly the capillary phenomena in the field, takes too much time to perform.

For this reason several other methods have been proposed. All of them are based upon the measurement of the surface tension of water only. However, since they disregard other important factors such as time, evaporation, etc., field measurements do not agree with those determined in the laboratory. In these methods the height of capillary rise (*passive capillarity*) is obtained by measuring the force applied to overcome the surface tension of water. The negative-head type of apparatus most commonly used to measure passive capillarity are the Beskow capillarimeter, and a modification proposed by the Public Roads Administration (Fig. 1). The latter apparatus described by the American Society for Testing Materials (1)[1] and the Highway Research Board (2) was used in our experiments. A suction force is applied by means of water, the level of which is gradually lowered in the outer glass cylinder. The height of capillary rise is taken as the distance between the top of the sample and the level of the water in the outer glass cylinder when the column of water in the inner tube breaks. Other devices are described in the Highway Research Board Proceedings, 1938, Vol. 18, Part II.

All the methods mentioned are based upon the so-called "capillary-tube hypothesis," in which the soil is considered as being composed of numerous capillary tubes. This hypothesis helps to determine the height of capillary rise

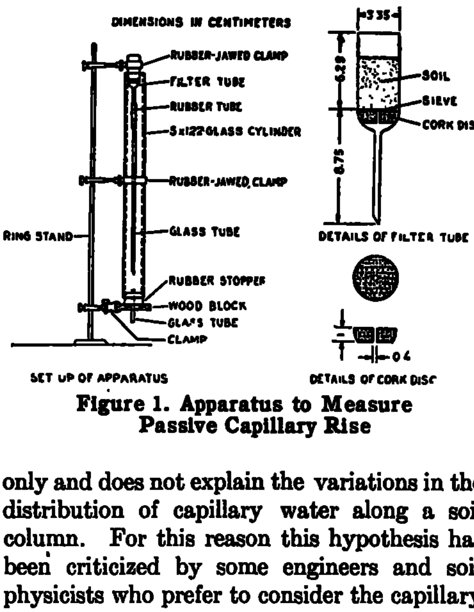

Figure 1. Apparatus to Measure Passive Capillary Rise

only and does not explain the variations in the distribution of capillary water along a soil column. For this reason this hypothesis has been criticized by some engineers and soil physicists who prefer to consider the capillary phenomena on the basis of the capillary-potential hypothesis, by which the flow of water in a soil is compared to the flow of heat within a metallic bar or to the flow of electricity through a wire. The capillary-potential hypothesis, pointed out by Buckingham (3) and others, shows that the distribution of the capillary water in a soil is a function of the height above the water level. However, in spite of its importance, this hypothesis alone cannot be successfully applied for engineering purposes.

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

It is my belief, therefore, that both hypotheses combined should lead the study of the capillary phenomena in soils. Neither one alone can explain the different stages of this complex phenomena. Thus, the height of capillary rise should be measured on the basis of the capillary-tube hypothesis, and the distribution of capillary water within a soil mass on the basis of the capillary-potential hypothesis. A further discussion of the latter hypothesis lies beyond the scope of this paper.

Theoretical Determinations. The height of capillary rise in soils (assuming the soil is composed of capillary-tubes) can be easily determined from the laws of Physics, since it is a direct function of the surface tension of water and inversely proportional to the diameter of the capillary tube. Hence:

$$h = \frac{4\sigma}{d} \qquad \text{Eq. 1}$$

Where:

- σ = surface tension of water in grams per cm.
- d = diameter of the tube in cm.
- h = height of capillary rise in cm.

Since the surface tension varies with temperature, it can be computed by means of the following formula given by N. E. Edlefsen and Anderson:

$$\sigma = 117.1 - 0.1516\,T \text{ dynes per cm.}$$
$$(1 \text{ dyne} = 1/981 \text{ grams})$$
$$T = 273 + t \text{ in deg. C.}$$

The Public Roads Administration suggested the following formulas to compute the diameter of particles and soil pores, and the height of capillary rise (5):

$$d = \frac{2d_1 \cdot d_2}{d_1 + d_2}$$
$$h = (2.9/d)^{0.92} \qquad \text{Eq. 2}$$
$$p = (d/2.4)^{0.92}$$

Where:

- d = mean diameter of grain, in mm.
- d_1 = sieve opening of the sieve which the fraction passes, in mm.
- d_2 = sieve opening of the sieve on which the fraction is retained, in mm.
- h = capillary rise in inches.
- p = mean diameter of soil pores.

In this paper the grain diameter was determined by taking the geometrical mean of d_1 and d_2; thus

$$d_s = \sqrt{d_1 \cdot d_2} \qquad \text{Eq. 3}$$

The values obtained for the height of capillary rise using the values for d and d_s are about the same as can be seen from Figure 2.

The diameter of the soil pores varies with the density of the soil and should be computed as a function of the void ratio e for a loose and dense state. For computing the average diameter of pores, Professor Tschebotarioff suggested the following formula:

$$d_p = e.d_s \qquad \text{Eq. 4}$$

Where:

- d_p = mean diameter of the soil pores, in mm.
- e = void ratio
- d_s = mean grain diameter, in mm.

In Figure 2 is plotted the height of capillary rise for d_p in both loose and dense state. The void ratio e was taken as 0.5 for sand in the densest state and 0.7 for sand in the loosest state. The results of these theoretical computations are indicated by parallel straight lines on the logarithmic scales of Figure 2.

The Passive and Active Capillary Rise. The exact relationship existing between the passive and active capillary rise was unknown so far. Franz Kögler was the first to state that the height of active capillary rise will be governed by the small openings and therefore will be larger than the height of passive capillary rise which should correspond to the wider openings only.

From Equation 1, we can infer that in dealing with granular material the larger the soil particle diameter the less the water will rise, or, in other words, small tension forces correspond to large pore openings. Thus, when a suction force, such as the increasing pull of a head of water is applied against surface tension forces in the water films of a soil, the least resistance will be present in the wider pores. The column of water held by surface tension will then break there first. The height of passive capillary rise, therefore, should correspond to the wider openings only and will not indicate the true capillary properties of the soil under conditions other than drainage.

On the other hand, for the height of active capillary rise we will obtain greater values because the water will rise higher in the small openings.

Kögler's statements in this matter are confirmed by the author's experiments. The results are shown on Figure 2. Tests were made on clean sand from Morrisville, Pennsylvania, separated into seven groups of uniform size by sieving through sieves Nos. 4; 6; 8; 14;

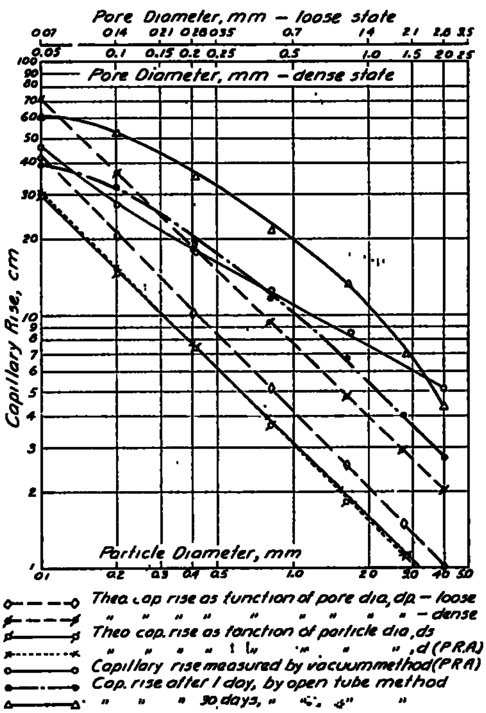

Figure 2. Comparison of Theoretical, Passive and Active Capillary Rise

28; 48; 100; 200. Note that some results give nearly 100 per cent difference between the observed heights of active and passive capillary rise.

It can be seen from the curves of Figure 2 that in the region of finer particles the height of passive capillary rise tends to increase rapidly, but the height of active capillary rise tends to increase much more slowly. This is probably due to the increasing relative thickness of the adsorbed water films. These films, which are held by molecular forces, are strongly attached to the soil particles by internal pressures of several thousand atmospheres. The water molecules subjected to such enormous pressures will be partially solidified, as pointed out by Dr. Winterkorn (4). This solidified water will seal the finest pores, thereby preventing the water from rising.

For reasons previously mentioned, the height of active capillary rise increases very slowly for finer cohesionless material, and possibly may even decrease in cohesive soils. This fact seems to explain why silts give higher values than clays for the height of active capillary rise when investigations are made in the field.

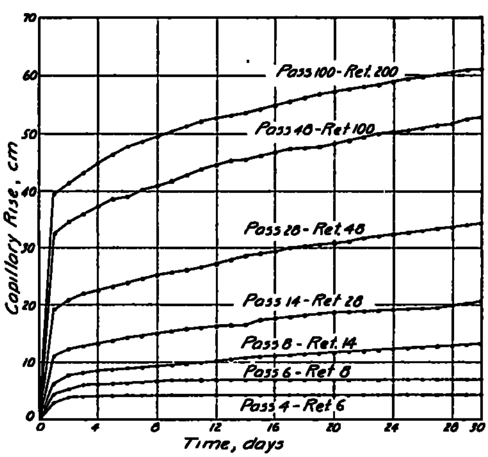

Figure 3. Capillary Rise vs. Time, Temperature 22 C., Humidity 60

On the other hand, if the height of passive capillary rise is to be determined in very fine soils, higher values will be obtained because a greater suction force will be necessary to break the water films in the solidified state. For this reason, the height of passive capillary rise tends to increase rapidly as the zone of cohesive soils is approached. One experiment we performed with a Vicksburg loess sample showed that the general trend obtained with sand samples and shown by the experimental curves on Figure 2 can be extrapolated into the region of silts.

Therefore, we can summarize by saying that the height of passive capillary rise will be lower than the active capillary rise in cohesionless materials but higher in cohesive soils. Further investigations should be carried out in cohesive soils to confirm this statement.

The Time Factor. The capillary rise is also a function of time. Consequently, no measurement of capillarity in soils should be taken without considering the time factor. Figure 3 shows that the different time-rise curves are nearly parabolic in nature, of the type $y = ax^b$.

Studying the rise of capillary water we can observe that the parabolic nature becomes more pronounced after the first day. Up to the first day there is a significant difference in the rise for each grain size. For this reason, we considered these curves as being of the type $y = ax^b + c$, taking the one day ordinate as origin and c as the capillary rise during the first day.

TABLE 1

Passing Sieve No.	Retained on Sieve No.	Capillary rise "y" in cm.	Capillary rise during the first day, "c", in cm.
4	6	$2x^{0 \cdot 10} + c$*	2.8
6	8	$2x^{0 \cdot 20} + c$	4.5
8	14	$2x^{0 \cdot 45} + c$	6.5
14	28	$2x^{0 \cdot 60} + c$	11.5
28	48	$2x^{0 \cdot 70} + c$	19.2
48	100	$2x^{0 \cdot 75} + c$	32.5
100	200	$2x^{0 \cdot 76} + c$	39.5

* x = time in days.

To compute the height of capillary rise as a function of time (other factors remaining constant), the equations in Table 1 have been established by the author for sands of different grain sizes.

Distribution of Capillary Water within a Soil Mass. Several attempts have been made to explain the distribution of capillary water through a soil, but neither the capillary-potential hypothesis nor the theory of the geometry of the pore spaces and the nature of the water films, as pointed out by Slichter, King, Haines and others have indicated a definite solution, and the conclusions at which they arrived are still far from being successfully used for practical purposes.

The distribution of capillary water through a soil column was studied by the author for sands of different grain sizes. As shown in Figure 4, there is a continuous and definite variation from a state of complete saturation near the free water surface, to a minimum degree of saturation at a certain height above the water level. All the curves indicate that there is a continuous relationship between the amount of soil moisture and the distance from the free water surface.

The curves show that for the same height above the water surface, the active capillary moisture content increases in finer material. It can also be seen that complete active saturation occurs only slightly above the water surface, and not up to the height of the passive capillary rise as is the common belief.

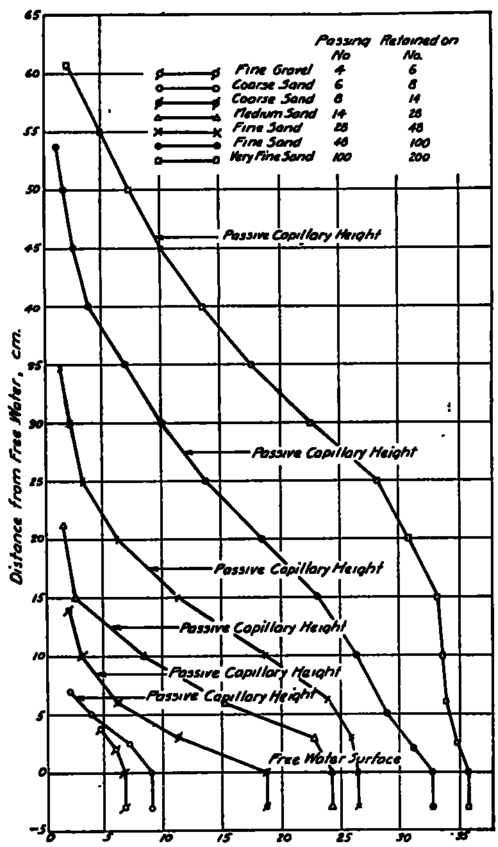

Figure 4. Distribution of Capillary Water

It is also interesting to note that the distribution of the capillary water obtained by draining a soil which has been previously submerged (passive capillarity) does not seem to follow the same trend as in the case when the water is allowed to rise through the soil column (active capillarity). Figure 5 shows this difference. There was a continued decrease with time of the passive capillary moisture content all along the height of saturation during the five days of observation. This happened in spite of the prevention of surface evaporation.

The same kind and grain size of sand was used during the tests.

Effect of the Mixture of Different Size Sand Particles on the Height of Passive Capillary Rise. In frost heaving problems it is important to establish the effect of finer material in soil mixtures. Tests relative to this matter were carried out by us with sand mixtures only. However, the results may be of some interest for further investigations.

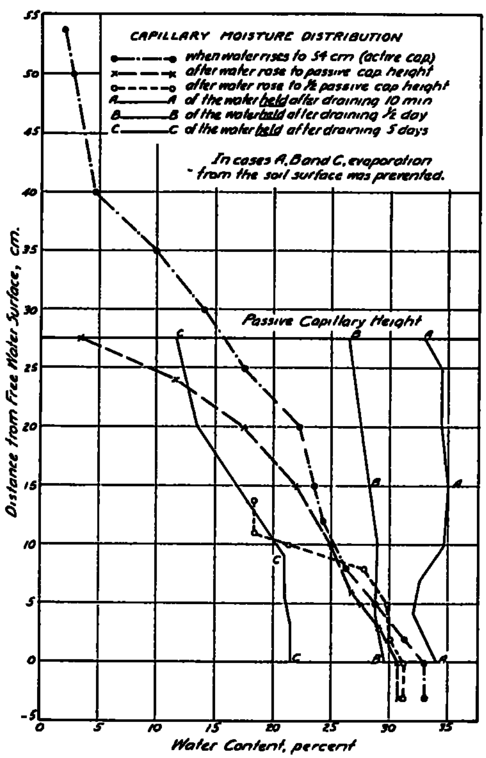

Figure 5. Capillary Water Distribution. Fine Sand Passing No. 48 Sieve, Retained on No. 100

The effect of finer material on the height of passive capillary rise for different mixtures is shown on Figure 6. The results seem to indicate that the finer material has a negligible effect when it constitutes less than 20 per cent of the volume of larger particles of uniform size. This fact is clearly shown in case 3 of Figure 6 when the finest grain size (passing sieve No. 100, retained on No. 200) was mixed with a medium size (sand passing sieve No 14, retained on No. 28). When both sizes were mixed in equal parts (50 per cent by volume), the medium grain size (the larger size in this case) had a greater effect, and the height of passive capillary rise decreased from 46 cm. (18.1 in.) to 14 cm. (5.5 in.), 12 cm. (4.72 in.) being the height of passive capillary rise for medium grain size.

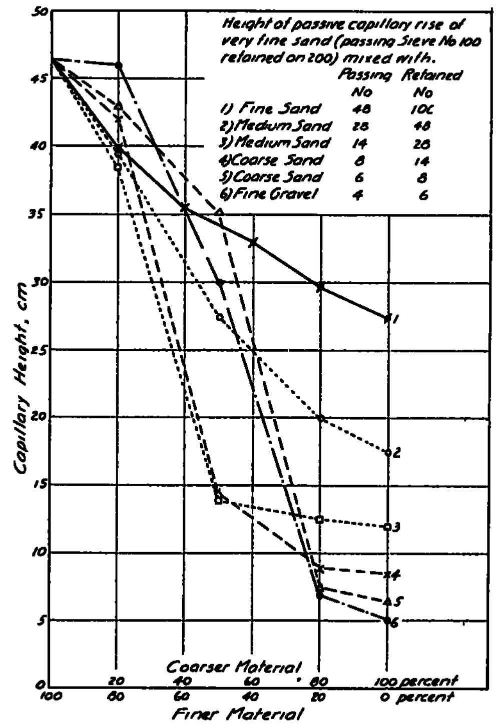

Figure 6. Passive Capillary Height in Sand Mixtures

From the several and different tests performed by the writer (Figure 6 shows one set of these tests only), we notice also that the height of passive capillary rise varies in an almost linear function when two successive grain sizes are mixed. In other cases the variation follows an inverted S curve between the two mixed sizes.

The Method of Test for the Determination of the Height of Passive Capillary Rise. In performing the tests by means of the method proposed by the Public Roads Administration, the following facts have also been found:

1. The same results were obtained by lowering the water in the jacket at a uniform rate of one cm. every 10 sec. instead of using the standard procedure. In this way time can be saved in performing the tests. Thus, as running the test by the standard method (lowering the water by 2-in. increments with a 5-min. pause between each increment) takes about an hour for very fine sand (sieves 100–200) it will take only about 10 min. in the manner previously mentioned, that is, by lowering the water at a uniform rate of one cm. every ten seconds.

2. The capillary rise varies with the height of the soil specimen in the filter tube. The tests performed with soil samples 1, 2, 3 and 4 cm. in height show that the height of passive capillary rise increases with increasing height of the soil specimen. To avoid this effect the height of passive capillary rise should be measured by taking the distance between the top of the water in the jacket and the bottom of the soil when the water column in the inner tube breaks.

Results of Practical Engineering Importance. From the experimental data outlined in this paper, the following facts can be established:

The study of the height of capillary rise should be approached on the basis of the capillary-tube hypothesis, and the distribution of moisture on the basis of the capillary-potential hypothesis. Both hypotheses, combined, should therefore lead the study of the capillary phenomena in soils.

Height of capillary rise

(*a*) The surface tension of water is not the only factor which governs the capillary phenomenon in soils. Several other factors such as time, evaporation, temperature, density of the soil mass and moisture content should be taken into account when the height or rate of the capillary rise is measured. The complexity of this phenomenon shows, therefore, that experiments performed in the laboratory have only a limited value because of the impossibility of exactly reproducing the field conditions.

(*b*) The capillary rise increases with time, relative air humidity, temperature, density of the soil, and fineness of the grain particles.

(*c*) The height of capillary rise in soils increases in a parabolic function with time.

(*d*) The height of passive capillary rise of coarse-grained sands corresponds to the wider openings only, and is therefore much smaller than the height of active capillary rise. In some cases the difference may amount to 100 per cent. The reverse relationship is true for finer grained materials. For this reason when the height of passive capillary rise is determined the results should be taken only with the limitations already established.

Distribution of capillary water

(*a*) Capillary water is not distributed uniformly in a soil mass. The water content decreases with the distance from the free water surface, from a complete saturation slightly above it to a minimum degree of saturation at the upper limit of the active capillary rise. Therefore, complete active capillary saturation is not present throughout the entire distance corresponding to the height of passive capillary rise.

(*b*) For the same height the capillary moisture content increases with the fineness of the particles.

(*c*) The capillary moisture distribution curve in a drained soil does not follow the same trend as in a soil saturated by active capillarity.

Sand mixtures

(*a*) In sand mixtures, the height of passive capillary rise varies almost in a linear function when two successive grain sizes are mixed. In other differently proportioned mixtures, the variation follows an inverted S curve between the two sizes mixed.

(*b*) In sand mixtures, finer material has a negligible effect on the height of passive capillary rise when its content is less than 20 per cent of the total volume.

Rate of capillarity

(*a*) Finer grained sands have higher rates of capillarity than coarse grained ones.

(*b*) The rate of capillary rise increases with relative air humidity and water temperature.

Test procedure

In performing the test to determine the height of passive capillary rise (Public Roads Administration method), the same results are obtained in much less time by lowering the water in the jacket at a uniform rate of one centimeter every ten seconds.

ACKNOWLEDGMENTS

The work reported in this paper had been performed under the direction of Professor Gregory P. Tschebotarioff of the Department of Civil Engineering at Princeton University. The author is gratefully indebted to him for all his constant supervision and help.

The author also wishes to acknowledge the assistance given him by Kenneth H. Condit, Dean of the School of Engineering, Professors Philip Kissam, Hans F. Winterkorn and Norman J. Sollenberger, all of the Department of Civil Engineering at Princeton.

LIST OF REFERENCES

(1) "Procedures of Testing Soils." American Society for Testing Materials, Sept. 1944, pp. 56 and 58.
(2) "War Time Road Problems—No. 8—Thickness of Flexible Pavements for Highway Loads," Highway Research Board, December, 1943.
(3) L. D. Baver, "Soil Physics," New York, 1940, (p. 197).
(4) H. F. Winterkorn, "The Condition of Water in Porous Systems," *Soil Science*, August 1943.
(5) C. A. Hogentogler and E. S. Barber, "Discussion on Soil-Water Phenomena, *Proceedings*, Highway Research Board, Vol. 41, p. 452, (1941).

DISCUSSION

Mr. C. A. Hogentogler, *Public Roads Administration:*

APPLICATION IN DETERMINING THE GRADING OF BACKFILL MATERIALS

In Wartime Road Problems No. 8 of the Highway Research Board (1)[1] reference is made to materials for use in drainage courses. Two kinds were proposed, namely, those for use at the interface with subgrade or other contiguous soil; and those suitable for use in all other parts of drainage mediums.

The "passive" capillary rise test referred to in Mr. Valle's report and a permeability test were suggested as means of determining suitable gradings of the granular materials. The capillary and permeability tests are described in Wartime Road Problems, No. 8, and also in Procedures for Testing Soils, American Society for Testing Materials (2).

Pertinent suggestions relating to properties of backfill materials are presented here principally for the purpose of stimulating thought and discussion on this vitally important problem.

Selection of porous materials suitable for use at the interface with soil to be drained, whether in sub-bases, drain trenches, sand drains or earth dams, involves two considerations. The porous material must be permeable enough to provide the desired drainage, and should have interstices small enough to prevent intrusion of the adjacent soil.

[1] Figures in parentheses refer to the list of references at the end of this discussion.

Desired drainage properties of materials depend on the type of structure, the available materials and, in large part, on the judgment of the engineer. Soil with a coefficient of permeability, k, less than 0.3 ft. per day, was considered suitable for use in the impermeable section of the Granville Dam (3). Soil with a value of k greater than 6.0 ft. per day was used in the pervious section, and soil with a k ranging from 0.3 ft. per day to 6.0 ft. per day was considered unsuitable for either section.

A fact finding survey of seepage by the Corps of Engineers, U. S. Army (4) furnishes additional information on impervious and pervious materials. The following is given for three earth dams:

Type of material	Coefficient of permeability, k, in ft. per day		
	Birch Hill Dam	Fort Supply Dam	Great Scott Plains Dam
Impervious	.03	.00015	.03
Pervious	15	6	30

H. E. Cotton (5) discusses materials suitable for use as backfill in drainage trenches, as follows:

"I have been recommending for a number of years the approximate grading of 80 per cent between ¼-in. and ½-in., 95 per cent passing the ¾-in., and 95 per cent retained on a No. 10 sieve, and it has been quite widely used. Occasionally, I am told that a drain located at so-and-so has ceased to function and that the backfill is either known to be or is supposed to be silted up. Invariably, the fact is that large size backfill was used. In the light of recent experiments, I am convinced that the backfill should be even finer than our past recommendations, especially where cohesionless fine sands and coarse silts are encountered."

Mr. Cotton makes specific reference to an investigation of protective filters by Captain G. E. Bertram (6), which resulted in a directive from the War Deprtment Office of the Chief of Engineers on the limiting gradation of backfill (7).

This directive includes a "piping ratio" as indicative of the possibility of the finer soil's intrusion of the porous material.

One expression used to indicate the absence of such possibility has the form

$$\text{maximum ratio, } \frac{A}{B} = 5$$

where A = maximum grain size of the smallest 15 per cent of well-graded backfill material, and

B = maximum grain size of the smallest 85 per cent fraction of well-graded adjacent soil

T. R. Agg (8) considers soils with a minimum k of 25 to 50 ft. per day as drainable by tile; and sandy clays with k less than 5 ft. per day as not readily drainable by tile.

Materials currently used in porous layers beneath pavements are considerably coarser than some of the pervious materials in earth dam construction, and somewhat coarser than indicated by the piping ratio for use adjacent to soils with high silt content.

As a compromise, a well-graded sand passing the No. 10 sieve and retained on the No 40 sieve is suggested as typifying properties desirable in stable, frost-free, and highly pervious sub-bases at the interface with the undersoil.

Relations between mean grain size, d, coefficient of permeability, k, and "passive" capillary rise, h, help depict the characteristics of granular material.

From those found by the Public Roads Administration (9) and given in Mr. Valle's report, it indicated that sand passing the No. 10 sieve and retained on the No. 40 sieve has a mean grain diameter, d = 0.695 mm., corresponding to h = 3.7 in. and k = 710 ft. per day.

The estimated maximum size of the smallest 15 per cent fraction of the sand suggested equals 0.57 mm. According to the piping ratio given above, there should be no danger of infiltration by undersoils for which the maximum size of the smallest 85 per cent is not less than 0.11 mm. Such undersoils should include the materials considered drainable by Professor Agg.

A passive capillary rise, h = 2 to 6 in., of the material passing the No. 10 sieve can be considered as indicating a practical approximation of the capillary and percolation properties of sand fraction suggested above.

This material should have corresponding coefficients of permeability, k = 2100 to 310 ft. per day.

It seems desirable also that the interface material have a minimum of 35 per cent of the stipulated sand fraction passing the No. 10 sieve. This is to insure that the pores of the coarse granular fractions be completely filled with the sand fraction. Except at the interface with the soil to be drained, all types of coarse granular materials should prove suitable for use.

It is pertinent to note that a filter material, considered safe from intrusion by contiguous soil, which was used in the Vicksburg experiments (4) had mechanical grading, as follows:

100 per cent passing ⅜-inch sieve
98 per cent passing Tyler No. 3 sieve
66 per cent passing Tyler No. 4 sieve
51 per cent passing Tyler No. 6 sieve
40 per cent passing Tyler No. 8 sieve
32 per cent passing Tyler No. 10 sieve
24 per cent passing Tyler No. 14 sieve
15 per cent passing Tyler No. 20 sieve
2 per cent passing Tyler No. 28 sieve

REFERENCES

1. Wartime Road Problems No. 8, "Thickness of Flexible Pavements for Highway Loads, Highway Research Board, December, 1943, see pp. 11, 12, and 13.
2. Procedures for Testing Soils, American Society for Testing Materials, September, 1944. See pp. 56 and 58.
3. "Soil Studies for the Granville Dam at Westfield, Mass." by Charles Terzaghi, *Journal*, New England Waterworks Association, June, 1939, p. 191.
4. "Seepage Studies," Technical Memorandum No. 175-1. U. S. Waterways Experiment Station, Vicksburg, Mississippi, March 1, 1941.

5. "Wet Subgrades, Their Cause and Cure," by H. E. Cotton, *Roads and Streets*, May, 1942, p. 42.
6. "An Experimental Investigation of Protective Filters," by G. E. Bertram, Graduate School of Engineering, Harvard University, January, 1940.
7. "Limiting Gradation for Backfilling Surrounding Drain Pipe," a Directive of the Office of the Chief of Engineers, War Department, December 18, 1941.
8. "Construction of Roads and Pavements," by T. R. Agg, McGraw-Hill Book Company, Fifth Edition, 1940, p. 88.
9. "Discussion on Soil-Water Phenomena," by C. A. Hogentogler and E. S. Barber, *Proceedings*, Highway Research Board, Vol. 41., p. 452 (1941).

ICE FORMATION ALONG THE ALASKA HIGHWAY

(In Abstract)[1]

By William L. Eager and William T. Pryor

Highway Engineers, Public Roads Administration

SYNOPSIS

Climatic, drainage and topographic conditions in subarctic regions as along the Alaska Highway cause ice formations that will invade the roadway surface in winter unless prevented. These formations are the result of water from seepage, springs, small streams, creeks and rivers emerging to the exposed surface where it spreads in thin film layers and freezes. Surface disturbances resulting from highway construction intensify this action.

It is impracticable to prevent icing entirely, and it is a difficult but performable task to keep the ice formations from invading the roadway where they are a hazard to and may stop traffic. During the winter of 1943–44 practices in ice control were developed and used to keep the road surface open to traffic throughout the winter.

Methods used and the various factors affecting ice formation are discussed. The influence of these factors on location, design, construction methods, and subsequent maintenance are pointed out.

The Alaska Highway extends from Dawson Creek, British Columbia, to Fairbanks, Alaska, a total length of 1,520 miles. Twelve hundred and twenty miles of the main highway is in Canada and 300 miles is in Alaska. Elevations range from 1,000 ft. above sea level at the Muskwa River near Fort Nelson to 4,251 ft. at the summit, 90 miles west of Fort Nelson. Most of the highway lies between elevations of 2,000 and 3,000 ft. It extends from about latitude 56° to 64° North and from about longitude 120° to 146° West. The area traversed is hilly or mountainous and for the most part is thickly timbered but the trees are generally too small to be of commercial value.

The highway was built during the period from March 1942 to November 1943. In 1942 seven regiments of U. S. Army Engineers, and 47 civilian contractors employing about 7,500 men working under the direction of the Public Roads Administration pushed through a pioneer road. Streams were bridged with temporary timber trestles not expected to withstand the spring break-up. The engineer troops were withdrawn from the highway before the beginning of the 1943 construction season with the exception of two companies that remained until July. Most of the permanent bridges required and an all-season gravel road suitable for heavy trucking were constructed during 1943 by 81 contractors employing about 14,000 civilian workers. These forces were directed by the Public Roads Administration.

[1] Reported more fully in *Public Roads*, January–February–March, 1945.