Development and Comparison of Permeability Measurement Techniques for Jointed Concrete Pavement Bases

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Prior research has shown that a well-drained base is a very important requirement for preserving the soundness of a highway pavement. Although adequate knowledge exists to guide an engineer in the design of a new pavement with good drainage characteristics, there are no established methods to estimate the quality of drainage under an existing pavement and therefore to estimate its life expectancy or to properly design its overlay. A summary is presented of research efforts aimed at investigating and adapting existing techniques from the geotechnical area for the development of methods for measuring the permeability of pavement bases. Two geotechnical methods were adapted, and one new technique was developed. The first two methods were used to conduct permeability tests near the middle of the pavement slabs, using either constant head or falling head setups. These were named the Midslab Constant Head Test Permeability Test and the Midslab Falling Head Permeability Test, respectively. The third method was designed for conducting permeability tests near the edge of a slab. This method was named the Edge-of-Slab Constant Head Permeability Test. Numerous permeability tests were conducted under a jointed reinforced concrete test pavement in Chillicothe, Ohio, using these three methods. It was found that the tests conducted near the edge of the slab held the most promise, even though the method needs further refinements. However, the results of the edge-of-slab test were quite different from those of the midslab test, partly because of the erosion of fines from the base in the edge-of-slab test. In addition, it became clear from the tests that the field test results were considerably different from laboratory test results.

A well-drained base is of utmost importance for highway pavements. Cedergren (*1*) in 1978 estimated that the lack of proper drainage of infiltrated water from the nation's highway pavements would cost U.S. taxpayers more than $200 billion in just 15 years. The AASHTO design guide (*2*) recognizes the importance of pavement drainage in its thickness design procedures by accounting for the quality of drainage and for the period of time during which the pavement section is exposed to moisture. However, the design guide does not help the engineer with criteria to establish what good quality drainage entails, especially when the rehabilitation of an existing pavement is in question. Nonetheless, engineering judgment points to the permeability of the base as one of the most important factors in pavement drainage.

The literature survey on the permeability of bases found several articles and references on the subject. Moulton and Seals (*3,4*) presented permeability testing methods applicable to the field measurement of permeability of newly placed bases and subbases before the pavement is placed on them. They designed a special permeameter device that is placed on (or driven into) the surface portion of the base or subbase. The method is not applicable to existing pavements.

There is also FHWA Demonstration Project 87 (*5*), which was designed to assist highway agencies in using new techniques in their design of permeable bases for concrete pavements.

The literature survey did not reveal accepted field procedures for finding the in-field permeability of existing base courses under concrete pavements. Therefore, concurrent with other research on a test pavement in Chillicothe, Ohio (*6*), a great deal of effort was spent on the development of appropriate in-field test procedures for finding the permeability of the base. Three different methods were tried and their results compared.

The test pavement on which permeability tests were conducted was built by the Ohio Department of Transportation in 1972 (*7*). It is a 983-m (3,225-ft) jointed portland cement concrete (JPCC) section in the southbound roadway on Route 23 in Chillicothe, Ohio. The pavement consists of two lanes 3.7 m (12 ft) wide separated by a longitudinal joint. The test section has 100 transverse joints. All slabs are 229 mm (9.0 in.) thick, and, except for a short segment, they are reinforced with wire mesh. The pavement is underlain by an embankment approximately 6.1 m (20 ft) high. Several variables were incorporated in the pavement: various joint spacings, type of base, type of dowel bar, and configuration of the saw cut. Table 1 gives details on the various sections of the pavement. The concrete slabs were supported on either a 191-mm (7.5-in.) thick granular base (Grade A, 310 material) or a 102-mm (4.0-in.) thick, Item 301 Bituminous Aggregate Base (ATB). Researchers at the University of Cincinnati studied the pavement between 1972 and 1980 and again between 1989 and 1992. Permeability tests were conducted only in the second phase of the study.

Although the test pavement was not designed for the purpose of evaluating the parameters that affect pavement drainage, the researchers undertook the task of investigating the as-is drainage characteristics of the portion of the pavement that was supported on granular base. From construction plans and field exploration, it was found that the test pavement had an edge collector drain consisting of one trench for the southbound two lanes, filled with pea gravel, and a drainpipe at the bottom.

In the permeability phase of the study, measurements were made on the granular base and the embankment subgrade material. The granular base was studied in both the laboratory and the field, whereas the embankment material was only tested in the laboratory. The permeability tests on the embankment were conducted

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TABLE 1 Details of Sections with Type of Joints, Base, and Dowel Bars

Section	Joint #	Number of Slabs	Slab Length m(feet)	Type of Base	Type of Dowels	Type of Joint (Depth & Type of Sawcut)
1	1 to 7	7	12.2(40)	Granular	Standard	3.2mm(1/8") Bevel
2	8 to 16	8	12.2(40)	Granular	Standard	6.4mm(1/4") Standard
3	17 to 24	8	6.4(21)	Stabilized	Standard	6.4mm(1/4") Standard
4	25 to 34	10	12.2(40)	Stabilized	Standard	6.4mm(1/4") Standard
5	35 to 44	11	5.2(17)	Stabilized	None	6.4mm(1/4") Standard
6	45 to 53	9	6.4(21)	Granular	Plastic Coated	6.4mm(1/4") Standard
7	54 to 63	10	12.2(40)	Granular	Plastic Coated	6.4mm(1/4") Standard
8	64 to 73	10	12.2(40)	Granular	Standard	12.7(1/2") Standard
9	74 to 84	10	12.2(40)	Granular	Standard	6.4mm(1/4") Standard
10	85 to 94	10	6.4(21)	Granular	Standard	6.4mm(1/4") Standard
11	95 to 96	2	12.2(40)	Granular	3M Coated	6.4mm(1/4") Standard
12	97 to 100	4	12.2(40)	Granular	Standard	6.4mm(1/4") Standard

Note: 1 m = 3.281 ft
1 mm = 0.0394 inch

to ascertain that it was much less pervious than the base, ensuring that water would flow only in the base during field tests.

The testing program started with in-field density tests and sampling of the base and subgrade materials for classification and Modified Proctor density tests. Laboratory permeability specimens were prepared, and permeability tests were run. Concurrently, field permeability tests were conducted on the ase at nine different locations along both lanes of the test pavement.

Pertinent details of the laboratory and field tests on the base and subgrade materials are presented in this paper, and the permeability test methods that were tried are evaluated.

MATERIALS AND METHODS

Field Sampling and Density Testing

A number of field samples were taken to conduct laboratory index, maximum density, and permeability tests. The base samples were taken at the edge of the pavement from locations directly under a joint or a crack. The sample locations are given in Table 2.

Two subgrade (embankment) samples were taken. Subgrade Sample 1 was taken from an area immediately below the pavement base near the location of Base Sample 7. Subgrade Sample 2 was obtained from a depth between 0.61 to 1.22 m (2.0 to 4.0 ft) below the surface of an area within the median adjacent to the shoulder at Joint 50.

In-place density determinations were made by a nuclear density meter on the base and the subgrade near the location of Base Sample 7.

Laboratory Soil Testing

Grain Size Distribution

Grain size distribution tests on the base and subgrade materials were performed in accordance with ASTM D-422. The sieve analysis results were used to obtain the percentages of gravel, sand, and fines (silt and clay) in each sample using Ohio Department of Transportation Classification Standards.

Modified Proctor Moisture-Density Tests

The Modified Proctor moisture-density relationship was determined for each of the base and subgrade samples according to ASTM D-698 standard procedures.

TABLE 2 Base Sample Designations and Locations

Sample #	Joint Location	Lane
1	14	Passing
2	45-1*	Passing
3	52	Driving
4	59	Driving
5	81	Passing
6	82	Passing
7	95-1*	Passing

Note: * indicates that the sample was taken at the first pavement crack south of the indicated joint, like Joint 45 or 95.

Laboratory Permeability

Laboratory permeability tests were performed on the base and subgrade samples. The test specimens were compacted in a 102-mm (4.0-in.) diameter Proctor test mold at optimum moisture content. The actual densities of the samples ranged between 91 and 99 percent of their Modified Proctor density. The permeability tests were conducted after the complete saturation of the samples in a falling head permeability test apparatus using deaired water. Each specimen was tested until its equilibrium permeability was reached.

Field Permeability Testing

Field permeability tests were conducted at nine selected locations in the test pavement. Specifically, tests were conducted under the pavement approximately midway between the following joints: 11 and 12, 46 and 47, 52 and 53, 56 and 57, 59 and 60, 80 and 81, 81 and 82, 94 and 95, and 95 and 96 (see Table 1 to identify the type of slab under which each test was conducted). As seen, these locations covered the length of the test pavement on granular base. All field permeability tests were conducted under segments that were in good to very good condition. Even though some of the slabs tested had shrinkage cracks, all permeability tests were conducted away from these cracks. Namely, if a test was run on a slab that was cracked, such as the slabs between joints 11 and 12, 56 and 57, 80 and 81, and 95 and 96, the test site was located midway between a crack and the joint or between two adjacent cracks.

Three different field test methods were used. The first two were designed to conduct permeability tests near the middle of the pavement slabs. They were named the Midslab Constant Head Permeability Test and the Midslab Falling Head Permeability Test, respectively. The third method was designed to test the permeability near the edge of the pavement. This method was named the Edge-of-Slab Constant Head Permeability Test.

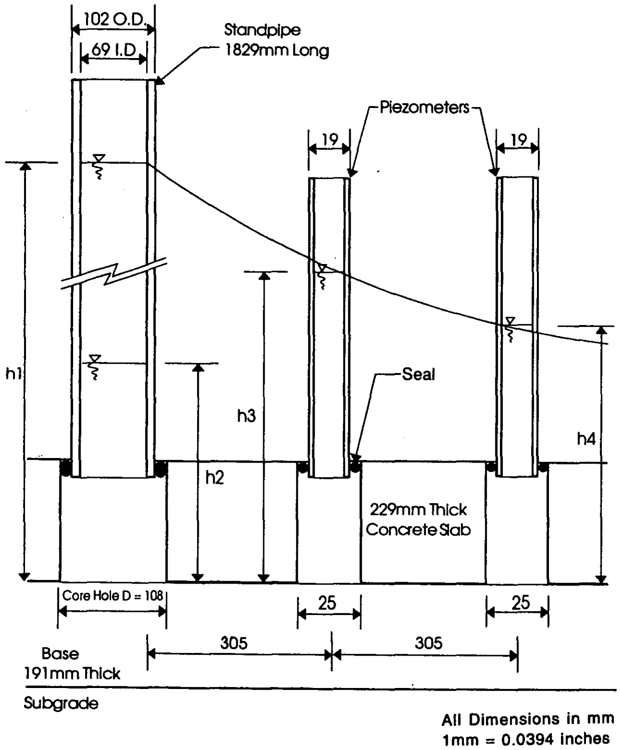


FIGURE 1 Side view of the midslab permeability test setup.

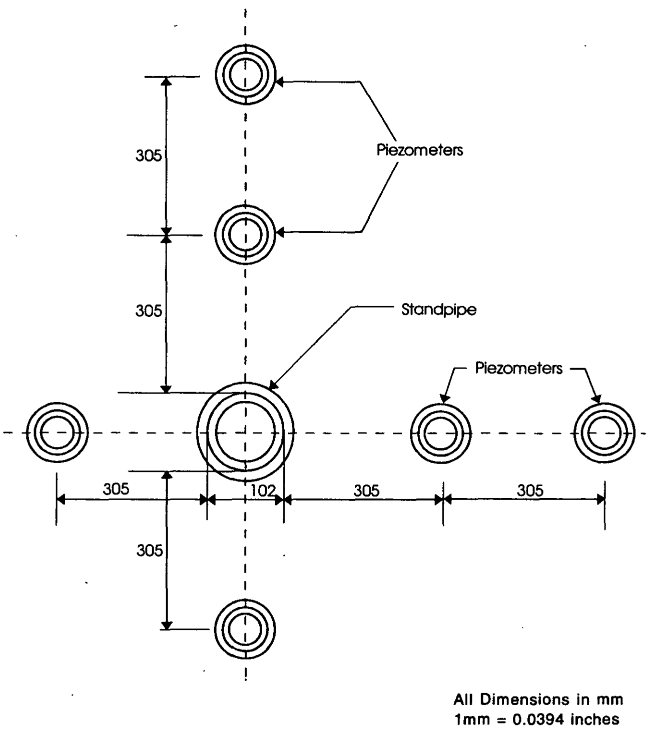


FIGURE 2 Plan view of midslab permeability test setup.

To initiate a Midslab Constant Head Permeability Test at a selected location, a 108-mm (4.25-in.) diameter hole was cored through the slab, and six 25-mm (1.0-in.) diameter holes were drilled through the slab adjacent to the core hole as shown in Figures 1 and 2. The holes were carefully cleaned of loose dirt. Into the core hole a 102-mm (4.0-in.) O.D. and 69-mm (2.719-in.) I.D., 1.83-m (6.0-ft) long acrylic tube was inserted. Acrylic tubes 19 mm (0.75 in.) O.D. and 0.6 m (2.0 ft) long were inserted in the 25-mm (1.0-in.) holes. The 102-mm (4.0-in.) tube served as a standpipe, and the 19-mm (0.75-in.) tubes were used as piezometers. The annular space between the tubes and the pavement was carefully sealed with rubber rings to prevent loss of water.

The tap water for running the tests was provided by Ohio Department of Transportation personnel from a 1.14-m^3 (300-gal) truck-mounted tank. The water was hosed by gravity into 3.8-L (1-gal) containers and then slowly poured into the 102-mm (4.0-in.) standpipe, carefully maintaining a constant head.

To find the permeability of the base material, the following formula was used:

$$k = Q(L)/dh(A)(t)$$

where

k = permeability of the base,
dh = average head drop between the inner and outer set of standpipes,

Q = measured quantity of outflow during time t,
A = cylindrical area of base section through which flow occurs between two sets of standpipes, and
L = radial distance between standpipes, typically 0.305 m (12 in.), as seen in Figures 1 and 2.

The tests at each location were conducted with two different standpipe heads. For each head, trial runs were conducted until the permeability reached equilibrium. The equilibrium water levels in the piezometers were recorded, together with the time it took to pour 1 gal of water into the standpipe.

The second field test, the Midslab Falling Head Permeability Test, was conducted with a falling water head in the standpipe. The equipment and technique were almost identical to those of the first method (see Figures 1 and 2) except that after the standpipe was filled, the time was measured for a selected drop in the water level in the tube and no attention was paid to the water level in the piezometers.

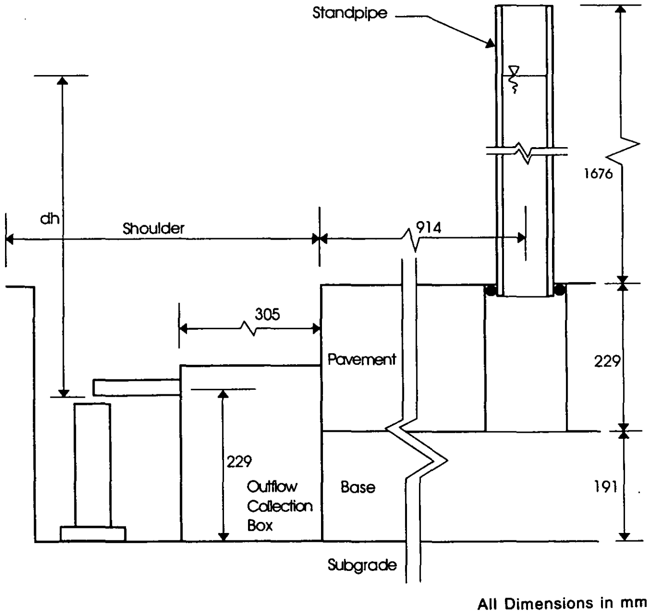
The permeability of the base was computed from the formula by Hvorslev (*8*), as presented by Daniel (*9*):

$$k = 3.14d^2 (\ln h_1 - \ln h_2)/11(D)(t)$$

where

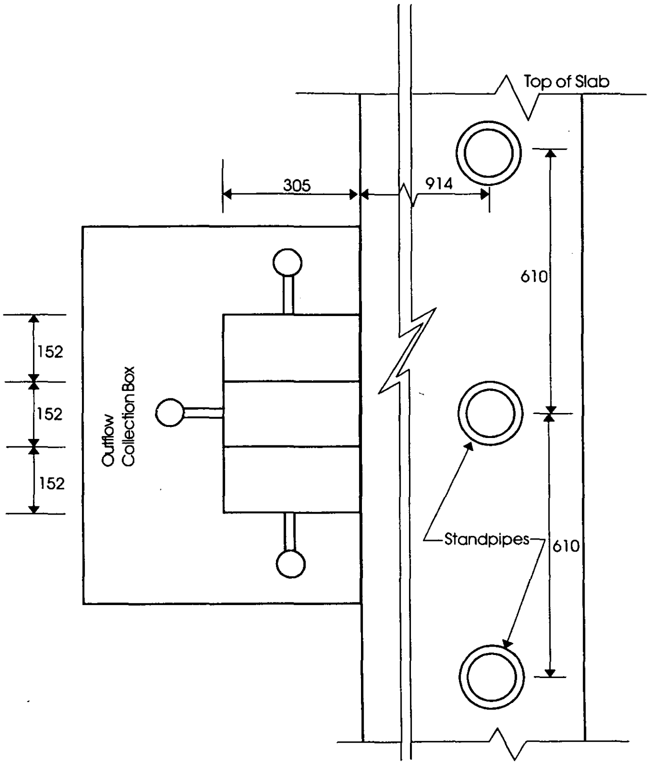
d = inside diameter of the tube,
D = diameter of core hole in pavement slab,
h_1, h_2 = head levels in standpipe at beginning and end of test, respectively, and
t = time duration of measurement (see Figures 1 and 2).

The third field test method, the Edge-of-Slab Constant Head Permeability Test, was conducted near the edge of the pavement slab. In this method, three standpipes were installed on a line approximately 0.91 m (3.0 ft) away from the pavement edge in holes cored through the concrete pavement and spaced at 0.61 m (2.0 ft) center to center. Each standpipe was an acrylic tube with 102-mm (4.0-in.) O.D., 69-mm (2.72-in.) I.D., and 1.83 m (6.0 ft) long. At the edge of the pavement, the shoulder was excavated and a filter fabric was placed on the exposed vertical face of the base. Against the fabric, an outflow collection box was installed. Figures 3 and 4 show the position of the tubes and the collection box. The permeability measurements were made by filling the three pipes to a predetermined elevation and then maintaining this level and observing the time required for a specific quantity of outflow at the edge of the pavement. The outflow was measured in the middle 152 mm (6.0 in.) of the 0.457-m (18-in.) wide outflow collection box. The role of the water from the outer two standpipes was to laterally confine and channel the flow from the center tube toward the edge of the pavement and into the 152-mm (6.0-in.) center portion of the outflow collection box. Part of the outflow from the side tubes was collected in the two side segments of the outflow box.



All Dimensions in mm
1mm = 0.0394 inches

FIGURE 3 Side view of the edge-of slab permeability test setup.



All Dimensions in mm
1mm = 0.0394 inches

FIGURE 4 Top view of the edge-of slab permeability test setup.

The permeability of the base was computed by the following formula:

$$k = Q(L)/dh(A)(t)$$

where

Q = outflow into collection box over selected time t,
L = distance between edge of pavement slab and center of three standpipes,

A = cross-sectional area of monitored flow channel, typically 152 mm (6.0 in.) wide by 229 mm (9.0 in.) high, and

dh = difference in head between water levels in tubes and outflow box.

In all three test procedures, it was assumed that water would flow down the standpipe tube or tubes, through the core hole, and then turn to spread out horizontally in the base material between the bottom of the concrete slab and the top of the subgrade. Since the subgrade had a permeability three orders lower than that of the base, it was assumed that it practically provided an impervious bottom boundary to the flow.

In every case, numerous trials were conducted. The reported values were from test results in which the permeability had equilibrated.

RESULTS

In-Field Density Tests

Two tests were performed in both the base and the subgrade. The average in-place dry density of the base material was 20.56 kN/m^3 (130.8 pcf), with a natural moisture content of 7.9 percent. The average subgrade dry density was 20.22 kN/m^3 (128.6 pcf), with a natural moisture content of 7.6 percent.

Index Test Results

From the grain size distribution data on seven base samples and using the Unified Soil Classification System, the base material can be described either as sand with silt and gravel or as silty sand with gravel. The fines content (silt and clay) ranged between 7 and 15 percent.

The subgrade soil samples (embankment soil) contained more silt and clay particles than the base material. The two samples had 16 and 27 percent silt and clay size particles, respectively. According to the Unified Soil Classification System, the samples may be described as silty sand with gravel.

The average maximum dry density of the base was found to be 21.20 kN/m^3 (134.9 pcf) with an average optimum moisture content of 7.1 percent. On the basis of the in-place density measurement near Base Sample 7, the pavement base was compacted to approximately 97 percent of its maximum Modified Proctor density.

Laboratory Permeability Test Results

The laboratory permeability tests on the subgrade soil gave values that ranged between 6.9×10^{-8} and 3.5×10^{-6} cm/sec (6.9×10^{-10} and 3.5×10^{-8} m/sec or 2.0×10^{-4} and 0.9×10^{-2} ft/day), with an average value of 2.6×10^{-7} cm/sec (2.6×10^{-9} m/sec or 0.74×10^{-3} ft/day). This indicated that the subgrade is quite impervious and capable of confining the drainage to the base course.

The laboratory permeability tests on the base material gave a wide variation in values. The probable reasons for this may have been the air trapped in the samples and, potentially, variations in the percentage of fines in the base material. The permeability values varied from 1.8×10^{-6} to 5.6×10^{-4} cm/sec (1.8×10^{-8} to 5.6×10^{-6} m/sec or 5.1×10^{-3} to 1.6 ft/day). The mean permeability value for the base samples was found to be 0.74×10^{-4} cm/sec (0.74×10^{-6} m/sec or 2.1×10^{-1} ft/day) when the material was compacted to between 97 and 100 percent Modified Proctor density.

Field Permeability Test Results

The results from the Midslab Constant Head Permeability Test are given in Table 3. These data show that the permeability of the base is surprisingly uniform over the full extent of the test pavement. With an average permeability value of 3.9×10^{-3} cm/sec, the maimum deviation was found to be only 1.8×10^{-3} cm/sec (1.8×10^{-5} m/sec or 5.1 ft/day). Also note that the use of two different heads gave practically identical permeability values.

The field permeability results for the base by the Midslab Falling Head Permeability Test are given in Table 4. The average permeability was found to be 3.9×10^{-3} cm/sec (3.9×10^{-5} m/sec or 11.1 ft/day), which is identical to the average permeability test results found from the constant head test. Similarly, the maimum deviation from the average was only 2.2×10^{-3} cm/sec (2.2×10^{-5} m/sec or 6.2 ft/day). Also, the two test sets with different heads gave very similar results.

It is important to note that the above two midslab permeability tests gave practically identical results that were fairly uniform along the full length of the test pavement.

The location and results of the four edge-of-slab constant head tests are given in Table 5. It is seen that the edge-of-slab permeability test results are about two orders of magnitude higher than those from the midslab tests. However, the edge-of-slab test results from different locations on the test pavement were again consistent, with a maximum deviation of only 1.6×10^{-1} cm/sec (1.6×10^{-3} m/sec or 4.5×10^{2} ft/day) from the average.

TABLE 3 Base Permeabilities from Midslab Constant Head Test

Location (between the joints given below)	Permeability with Head A, (cm/s)	Permeability with Head B, (cm/s)
11-12	2.1 x 10^{-3}	1.7 x 10^{-3}
46-47	3.6 x 10^{-3}	-
56-57	4.4 x 10^{-3}	-
80-81	5.7 x 10^{-3}	5.7 x 10^{-3}
Average (all joints):	3.9 x 10^{-3} (11.1 ft/day)	

Note: 1 cm/s = 0.01 m/s =2.835x10^3 ft/day

TABLE 4 Base Permeabilities from Midslab Falling Head Test

Location (between the joints given below)	Permeability with Head A, (cm/s)	Permeability with Head B, (cm/s)
11-12	2.3×10^{-3}	1.7×10^{-3}
46-47	4.4×10^{-3}	-
56-57	3.9×10^{-3}	-
80-81	5.7×10^{-3}	5.7×10^{-3}
95-96	3.0×10^{-3}	-
Average (all joints):	3.9×10^{-3} (11.1 ft/day)	

ANALYSIS

Both midslab test results show a remarkable consistency along the full length of the test pavement. Also, there was good consistency between the results from tests with two different heads. Comparison of the results from the midslab constant head and falling head permeability tests revealed that the average values from the two were identical at 3.9×10^{-3} cm/sec (3.9×10^{-5} m/sec or 11.1 ft/day).

The edge-of-slab test was designed to simplify the flow pattern in the base and to increase the accuracy of the permeability test. This was achieved by the simple geometry of flow with well-defined boundaries. The method gave consistent values along the length of the test pavement, but the values were considerably higher than those from the midslab tests. Namely, the edge-of-slab test gave an average permeability of 2.0×10^{-1} cm/sec (2.0×10^{-3} m/sec or 5.7×10^{2} ft/day), versus the midslab test average of 3.9×10^{-3} cm/sec (3.9×10^{-5} m/sec or 11.1 ft/day). There may be several reasons for this difference. The edge-of-slab permeability may have been higher than the midslab permeability because of observed erosion of the finer particles from the base near the edge and the potential slumping of the base material under the pavement edge during the test. Conversely, it is possible that the permeability of the base at midslab is lower than that at the edge because of deposits of fines in this area from infiltrating rainwater and its slow flow. The low quantity of flow near the midslab may also result in a state of partial saturation with entrapped air, thus in lower permeability. This state of partial saturation may have prevailed during field testing, even though close to 1.14 m^3 (300 gal) of water was used for a typical test. At this time it is difficult to reconcile the difference between test results from the two methods. Most probably the true base permeability lies between the results from the two tests, and perhaps both types of tests should be run routinely.

It is believed that the edge-of slab test holds great promise, but more field research is needed to refine it. One aspect of the test that needs improvement is the leakproofing of the contact surface between the outflow collection box and the base material to increase the accuracy of outflow measurement. Also, a well-designed filter fabric should be used on the contact surface to minimize the erosion of fines. Another way of improving the method would be to make the outflow collection box very sturdy and to drive it firmly into the base at the edge of the pavement slab. This would ensure a tight fit between the box and the base that would eliminate slumping. Measuring the outflow while maintaining an equilibrium water level in the three sections of the box was difficult. Specifically, the water levels had to be kept constant and at the same elevation to prevent crossflow among the three sections.

In general, there is a need to consider a less destructive approach for the field tests. Drilling smaller holes through the pavement and using smaller-diameter standpipes may be one way of achieving this.

The laboratory permeability results yielded values that were considerably lower than those of the three types of field tests. One cause may have been that in the laboratory samples, air was trapped in the voids that blocked the flow. Another explanation may be that the laboratory samples were taken from an area near the joints where the base material may have contained more fines than the area under the slab, resulting in lower permeability. Yet another reason may be the existence of flow channels between the base and the bottom of the pavement, causing the higher field permeability. In a similar vein, another reason for higher field permeability may be the separation between the pavement slab

TABLE 5 Base Permeabilities from Edge-of-Slab Constant Head Test

Location (between joints given below)	Permeability (cm/s)
52-53	3.6×10^{-1}
59-60	2.6×10^{-1}
81-81	0.8×10^{-1}
94-95	$1.1 \times {}^{-1}$
Average (all joints):	2.0×10^{-1} cm/s (5.7×10^{2} ft/day)

Note: 1 cm/s = 0.01 m/s = 2.835×10^{3} ft/day) and the base during curling caused by temperature gradients. This could have caused sheet flow just below the slab, especially near the midslab at midday, at which point and time most of the field permeability tests were conducted.

The above differences point to the necessity of field tests. Even if laboratory tests are conducted on carefully obtained samples, the tests just cannot simulate the in situ conditions, such as air content, accumulation of fines, and flow channels.

CONCLUSIONS

No established field methods are currently available to determine the in situ permeability of the base under an existing pavement. This research made moderate progress in identifying and testing some of the promising field methods that may be used for base permeability tests.

The use of the methods that were investigated is limited to cases in which the base has a considerably higher permeability than the underlying subgrade. This condition is necessary in order to confine the flow to the base.

In principle, both midslab and edge-of-slab tests should measure the permeability of the base to an acceptable level of accuracy. Yet there was a large difference in the permeabilities found at midslab and at the edge of the pavement. As described in the analysis section, this difference may be caused by entrapped air or flow under the middle of the slab or by erosion of fines and slumping of the base at the edge of the slab and the consequent increase in flow rate. Through engineering judgment, it is estimated that the field permeability of the base tested lies between the values obtained from the two test methods (midslab and edge-of-slab). However, it is recommended that for design purposes the more critical midslab permeability value be used.

In the authors' opinion, the edge-of-slab constant head test needs further investigation and refinement. It would be the favored method since the geometry and mechanism of flow are relatively simple and fully tractable. It is recommended that the contact area between the outflow collection box and the base material be provided with a well-designed filter fabric to minimize the erosion of fines from the base. Also, the use of a small water head is recommended for the same reason. In addition, the collection box could be made sturdier and driven into the base at the edge of the pavement slab to ensure minimum disturbance to the base and provide a tight outflow surface. Furthermore, smaller standpipes should be used to reduce the size of the cored holes in the pavement and the resulting damage.

It will be necessary to narrow the difference between laboratory and field permeability test results. Ways to do this may include increased care in sampling and careful preparation of permeability samples, such as compacting them under water to ensure complete saturation. It is recommended that companion testing be done on the base material in each area (midslab and edge-of-slab) by both field and laboratory methods. It is also recommended that laboratory samples be taken from the area to be tested before and after the field tests to observe any changes in their fines content and, potentially, to run laboratory permeability tests on both types of samples.

This research produced some interesting findings, but it also showed considerable discrepancies in the results between the two main field methods, as well as between field and laboratory testing. It also emphasized the fact that laboratory tests are not adequate in characterizing the base material and that field permeability tests are necessary. The results indicate that further research should be conducted to improve the consistency between the two main methods of field testing (midslab and edge-of-slab) and to attempt to narrow the difference between the laboratory and field permeability data.

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