Estimating Permeability of Asphalt-Treated Bases

JAY K. LINDLY AND ASHRAF S. ELSAYED

This report describes laboratory testing and statistical analysis of the resulting data to determine the effects of aggregate gradation and percent asphalt stabilization on the permeability of asphalt-treated roadway base layers. Three different types of aggregates were tested in the study. They are crushed limestone, crushed granite, and uncrushed river gravel. A top size of 38 mm (1.5 in.) was used for all gradations. Asphalt cement (AC-20 grade) at 2 percent and 3 percent was used to stabilize the aggregates. A total of 60 permeability tests were performed using a 15.2 cm (6-in.) diameter permeameter. A statistical method was used to arrive at a first-order multiple regression equation to predict the coefficient of permeability of asphalt-treated bases in the range of 0.2–0.7 cm/sec (500–2,000 ft/day) using the percentage of air voids in the sample, the percentage of asphalt cement used, and the percent by weight of materials that pass the 2.36-mm (no. 8) sieve.

Highway personnel agree that excess water in pavements is one of the primary reasons for premature roadway failures. Excess water reduces the frictional strength of the structural section and foundation materials by creating buoyancy within these materials (*1*). Excess pore water pressure can be created within subgrade and pavement structural elements by wheel impacts (*2*). These situations can produce excessive deflection, cracking, reduction in load-carrying capacity, raveling and disintegration of asphalt mixes, subgrade instability, pumping, and loss of support (*1,3*).

Water can enter the pavement structure by means of infiltration through the pavement surfaces and shoulders, melting of ice lenses during the freezing/thawing cycle, capillary action, and seasonal changes in the water table (*2,4,5*). It was the common belief that high water table and capillary water are the primary causes of excess water in pavement. However, recent studies indicated that surface (infiltration) water is the main cause of moisture accumulation in the subgrade (*2*).

DAMAGE MINIMIZATION

Two methods are used to minimize the moisture-induced damage in pavement systems. The first method is to prevent the moisture from entering the pavement system by sealing the joints and using impervious surface layers. As pavements age and cracks multiply, this method becomes more impractical and expensive. The second method involves draining the excess moisture which enters the pavement system as quick as possible. Drainage is accomplished by employing high permeability base (or subbase) layers which are daylighted or which flow into discharge pipes (*4,5*). This method is dependent on the permeability of the base and/or subbase layer. Permeability is measured using Darcy's law. The more permeable the layer is, the quicker it drains the excess moisture.

Dense graded bases as currently specified do not have the required permeability to drain the pavements as quickly as designers wish. So, designers started using open-graded, highly permeable layers to provide the required drainage capabilities. However, a highly permeable layer can result in construction and rutting problems due to its low stability (*6,7*). One solution to that problem is to stabilize the open-graded layer with 2–3 percent asphalt cement to provide the necessary stability for construction and to minimize the future rutting under heavy traffic (*8–10*).

Many highway agencies have set permeability specifications for asphalt-treated permeable layers to be used in the drainage design of highway structures. The drainage design is usually based on a coefficient of permeability in the range of 0.18–0.36 cm/sec (500–1,000 ft/day). However, because of the variability involved in the testing and the construction of the drainage layers, the designers prefer that these layers have a much higher laboratory permeability than the range mentioned above.

Another reason for specifying a laboratory permeability much higher than the design range is that the coefficient of permeability is calculated in the lab in a 100 percent saturation condition, which gives higher coefficients than lower saturation conditions. One hundred percent saturation is rarely reached in the field. So, the drainage layers are usually developed based on a lab permeability of 0.4–2.0 cm/sec (1,000–5,000 ft/day), with the range of 0.8–1.2 cm/sec (2,000–3,000 ft/day) commonly used. Higher values of the coefficient of permeability are desired, but anticipated rutting and construction problems prevent the designers from using higher permeability layers.

To save time, the designer may want to estimate the laboratory coefficient of permeability of the drainage layer under specified gradation, density, and porosity conditions to use for the analysis and the design of a drainage system. (He can later perform laboratory tests on the final gradation and asphalt content he has selected.) There have been a number of charts and nomograph developed for estimating permeability of untreated aggregates. Two of the most well known are a chart by Cedergren (Figure 1) (*11*) and a nomograph by Moulton (Figure 2) (*12*). The only tool for predicting permeability of asphalt-treated bases found in the literature is Table 1 from Lovering and Cedergren (1962) (*11*). No study was found which employed the typical gradations used in today's treated bases or which varied the asphalt content.

PURPOSE OF THIS RESEARCH

The purpose of this research is to find a method to predict the laboratory coefficient of permeability of asphalt-treated bases for different aggregates, at a range of 2–3 percent asphalt, and at gradations typical of those used in modern construction.

Civil Engineering Department, University of Alabama, P.O. Box 870205, Tuscaloosa, Ala. 35487–0205.

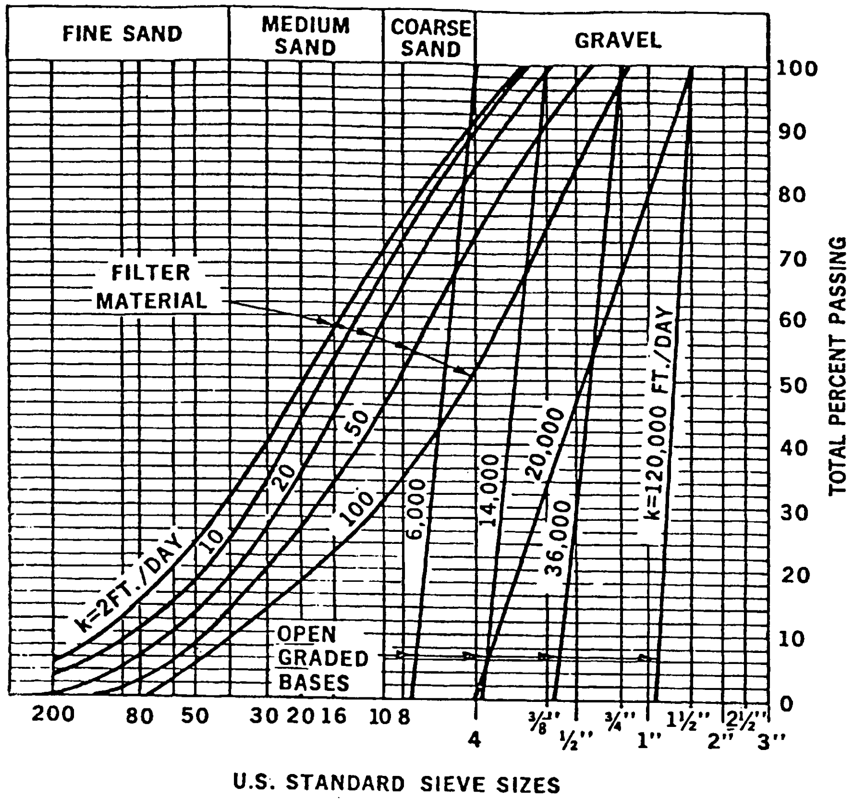
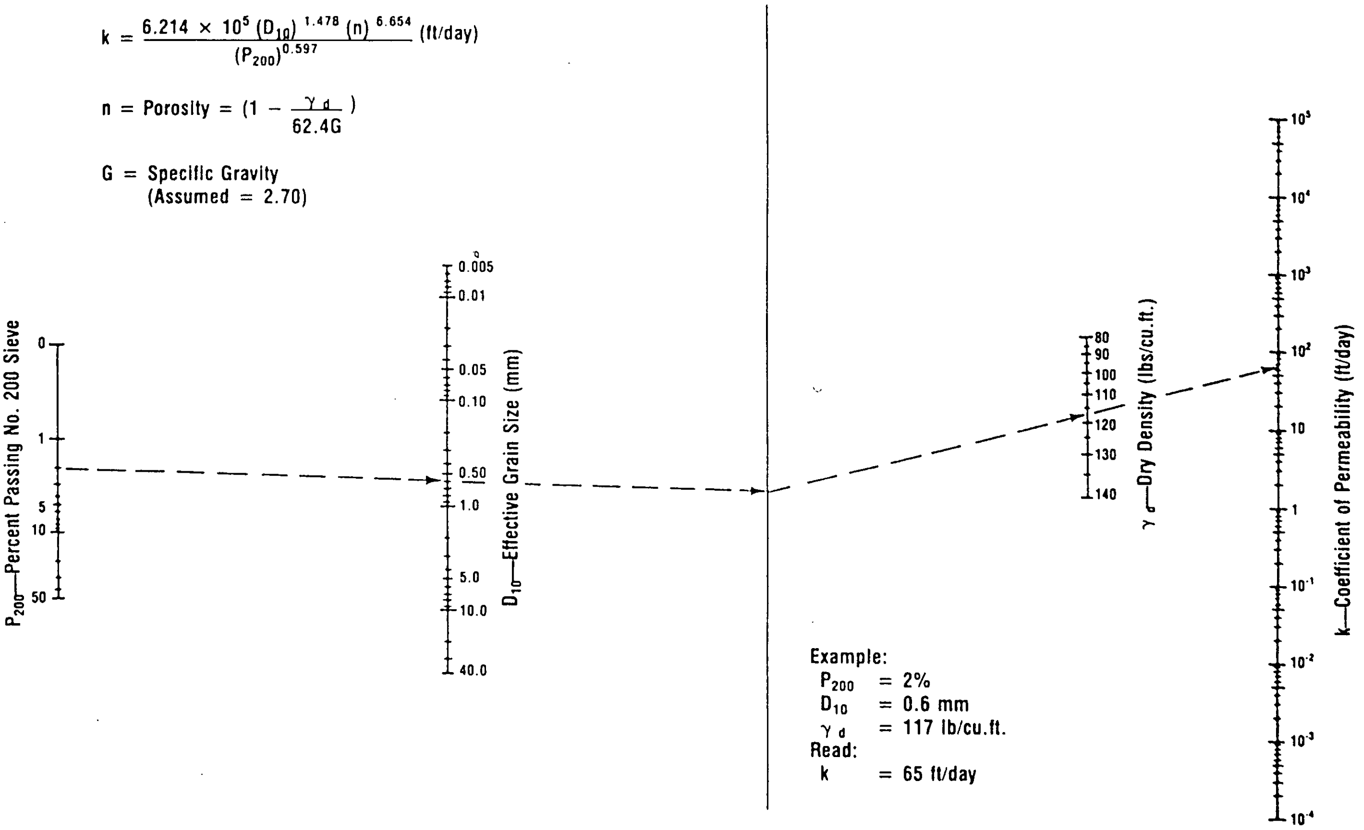


FIGURE 1 Cedergren chart.



$$k = \frac{6.214 \times 10^5 (D_{10})^{1.478} (n)^{6.654}}{(P_{200})^{0.597}} \text{ (ft/day)}$$

$$n = \text{Porosity} = \left(1 - \frac{\gamma_d}{62.4G}\right)$$

G = Specific Gravity
(Assumed = 2.70)

Example:
P_{200} = 2%
D_{10} = 0.6 mm
γ_d = 117 lb/cu.ft.
Read:
k = 65 ft/day

FIGURE 2 Moulton nomograph.

TABLE 1 Laboratory Permeability of Untreated and Asphalt-Stabilized Open-Graded Aggregates

Average size range	Permeability (ft/day)	
	Untreated	Bound with 2% asphalt
1.5 to 1 in.	140,000	120,000
3/4 to 3/8 in.	38,000	35000
No. 4 to No. 8	8,000	6,000

(Lovering and Cedergren, 1962)

MATERIALS, DESIGN OF EXPERIMENT, AND TEST PROCEDURES

The materials tested, the number and type of tests, and the design of the experiment can be described under the following headings.

Materials

All aggregates used in the study were provided by Vulcan Materials Company (VMC) in Birmingham, Ala. Three aggregates were tested:

a. Dolcito limestone from VMC quarries near Birmingham, Ala. It has a specific gravity of 2.71 and a top size of 38 mm (1.5 in.).

b. Crushed granite from VMC quarries in Georgia. It has a specific gravity of 2.67 and a top size of 38 mm (1.5 in.).

c. Uncrushed river gravel from VMC quarries in Chattanooga, Tenn. It has a specific gravity of 2.44 and a top size of 25 mm (1.0 in.).

The asphalt cement used in the study was AC-20 grade. It was provided by Hunt Refinery in Tuscaloosa, Ala.

Permeameter

The permeameter used in the study was built in the machine shop of the University of Alabama College of Engineering. This permeameter was designed to determine the coefficient of permeability under the low hydraulic gradient conditions found in highways and was introduced by Barber and Sawyer (*13*) in 1951. This permeameter has also been successfully used in the Pennsylvania Department of Transportation research facilities (*14*). The permeameter built had a 15.2 cm (6 in.) inside diameter, which is suitable for testing materials up to 38 mm (1.5 in.) top size. Figure 3 shows the permeameter and the associated equations used to determine the coefficient of permeability. The derivation of these equations was explained by E. G. Yemington (*15*) in 1963.

Gradation Selection

Two gradations were developed to be used in the study. The first gradation was developed to give a coefficient of permeability of 0.18 cm/sec (500 ft/day). This gradation is similar to the gradation developed by the New Jersey DOT (*16*) which has a permeability of 0.36–0.54 cm/sec (1,000–1,500 ft/day). Then, the 0.18 cm/sec (500 ft/day) gradation was modified (mainly by reducing fines) to produce a 0.71 cm/sec (2,000 ft/day) gradation. The two gradations are shown in Table 2.

Design of Experiment

The design of experiment can be summarized as follows:

a. Asphalt percentages of 2 and 3 percent were used.

b. Three different aggregates were used (as mentioned before).

c. Two different gradations were used (as discussed before).

d. Five repetitions were performed at each asphalt content and gradation. This provides a full factorial experiment, resulting in 60 test specimens.

e. An average of six measurements of the coefficient of permeability were taken for each test specimen.

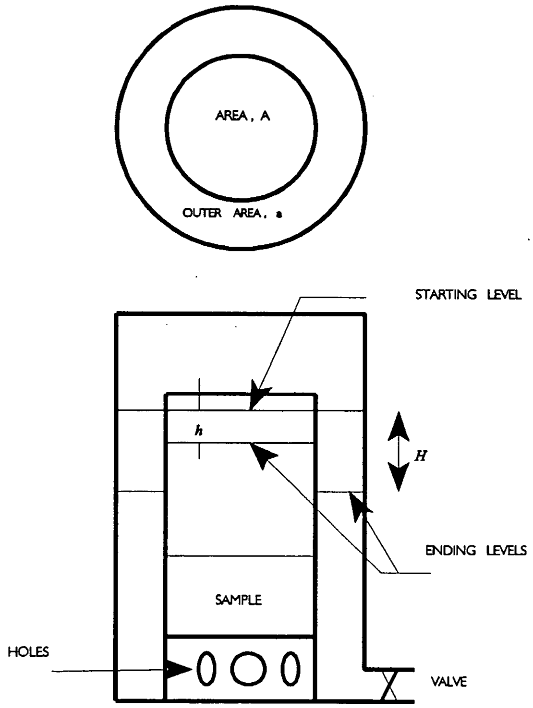
Test Procedure

The procedure described in the Asphalt Institute MS-2 (*17*) was followed for combining the aggregates and asphalt cement into test specimens. Because of the lack of fines in the test specimens, the standard hammer was not used for compaction, as it would have crushed the large aggregate pieces as well as pumped the asphalt to the surface of the sample. Instead, a static load of 20,000–22,000 kg (55,000–60,000 lb) was applied using a hydraulic jack to arrive at the required compaction. The load was applied until the sample reached a pre-set height, calculated to give a unit weight in the desired range. This range was 2,040–2,220 kg/m^3 (125–140 lb/ft^3) for the limestone, 1,950–2,100 kg/m^3 (120–130 lb/ft^3) for the granite, and 1,700–1,800 kg/m^3 (105–115 lb/ft^3) for the uncrushed river gravel.

Before conducting the permeability test, the net weight and the average height of each sample were calculated so that the unit weight of the sample could be determined.

TEST RESULTS

Test results were summarized in 12 tables: one for each combination of aggregate, gradation, and asphalt content. Table 3 is an example of one of these 12 tables. It shows the following data types:



$$K=\frac{F}{1-\frac{hS}{Q}}*\frac{ad}{St}$$

F can be calculated using the equation:

$$\frac{hS}{Q}=1-\frac{F}{\ln\frac{1}{1-F}}$$

Q = the outflow volume caught in time t,
S = A + a,
h = the drop in water level inside the inner cylinder,
d = sample height,

FIGURE 3 The permeameter used in the study.

TABLE 2 Gradations Used in the Study

Sieve Designation	500 fpd gradation % pass by wt.	2000 fpd gradation % pass by wt.
1.5	100	100
1	93-100	89-100
3/4	80-90	70-80
1/2	60-72	50-62
3/8	52-62	38-52
4	33-41	13-34
8	15-22	2-18
16	0-7	0-6
30	0	0

TABLE 3 Example of Test Results

Permeability Testing					
500 fpd Trial					
Dolcito Limestone-3% A.C.					
Summary of Lab Results					
1-Grain Size Distribution					
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Sieve	% Passing	% Passing	% Passing	% Passing	% Passing
1.5	100	100	100	100	100
1	94	94	94	94	93.9
3/4	79.9	79.9	79.9	80	79.8
1/2	61.8	61.7	61.8	61.9	61.7
3/8	51.7	51.7	51.7	51.9	51.6
4	33.6	33.5	33.6	33.9	33.4
8	17.4	17.4	17.5	17.9	17.3
16	4.4	4.3	5.5	3.8	4.2
30	0	0	0	0	0
Permeability Values in cm/sec (fpd)					
cm/sec	0.196	0.173	0.044	0.245	0.212
fpd	557	491	126	695	600
Dimension, cm					
Ht.	13.2	13.06	12.73	13.32	13.0
Diam	15.2	15.2	15.2	15.2	15.2
Unit Weight					
pcf	132.9	134.2	138.5	132.3	134.7
g/cm^3	2.13	2.15	2.22	2.12	2.16
A.C. %	2.7	2.7	3.1	2.7	2.7

a. The table heading contains the target permeability, the type of aggregate tested, and the desired asphalt content.

b. Each column in the body of the table contains the data for one of the five replicates of this combination of asphalt content, gradation, and aggregate type. The grain-size distribution, the average calculated coefficient of permeability, the average height, the diameter, the unit weight, and the exact asphalt percentage (by aggregate weight) for each sample are given.

DATA ANALYSIS AND RESULTS

The researchers listed the factors they thought might significantly affect the laboratory determination of the coefficient of permeability:

a. The percent air voids in each sample.

b. The percent asphalt in each sample, by total weight.

c. The crush factor (crushed versus uncrushed aggregate).

d. The percent passing, by weight, through sieves 0.6, 1.18, 2.36, 4.75, 9.5, 12.5, and 19.0 mm (nos. 30, 16, 8, 4; 3/8, 1/2, and 3/4 in.).

The viscosity of water was not taken into consideration since it depends on the water temperature, which was constant and equal to the laboratory temperature (25°C).

The percent air voids accounts for the total volume through which water can flow inside the sample and was assumed to be a very important factor in the experiment. Air void values were calculated following the procedure described in the Asphalt Institute MS-2 specifications.

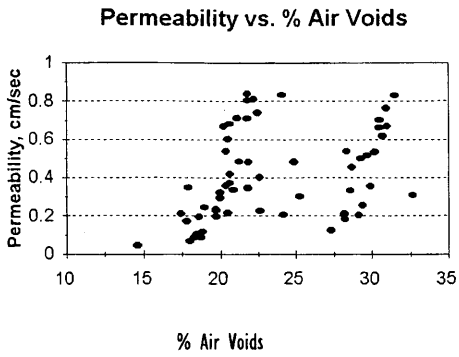


FIGURE 4 Permeability versus percent air voids.

The crushed materials were assigned a crush factor of 3, whereas the uncrushed materials were assigned a crush factor of 2. However, statistical analysis (described later) indicated that the crush factor has no significant effect on the coefficient of permeability, perhaps because the asphalt coating eliminated the angularity effect and made the aggregates behave as semi-angular or round aggregates in the permeability tests.

The statistical analysis also indicated that the percentage of coarser material (the amount retained on the 4.75-mm (no. 4) sieve did not have a significant effect on the permeability. The finer part (the amount passing the 4.75-mm (no. 4) sieve) is the part that affects the volume of voids inside the sample and consequently affects the coefficient of permeability. So, only the percentages passing 4.74-, 2.36-, 1.18-, and 0.6-mm (nos. 4, 8, 16, and 30) sieves were taken into consideration as statistical analysis continued.

In this manner, the insignificant factors were eliminated, and only the important factors were included in the reminder of the statistical analysis:

a. Percent air voids.
b. Percent asphalt.
c. Percent passing 0.6-, 1.18-, 2.36-, 4.75-mm (nos. 30, 16, 8, and 4) sieves.

A computer program called EXACUSTAT was used to conduct the regression analysis. A permeability coefficient was chosen as the dependent variable, and the other factors were treated as independent variables. First, each factor was plotted against the coefficient of permeability, *k*, to find if there was a trend in the relationships between *k* and the different factors. Figure 4 is an example of these plots, and it shows the relationship between *k* and the percent air voids. Figure 4 also shows a trend for two groups of points around 20 and 30 percent air voids. To investigate this observation, a correlation analysis was run on all the independent variables that were used in the regression analysis (discussed later). The results of the correlation analysis, which are shown in Table 4, indicated almost no correlation between percent asphalt and percent passing 2.36 mm (no. 8) sieve (correlation coefficient of −0.0453), slight correlation between percent air voids and percent asphalt (correlation coefficient of −0.1388), and a considerable correlation between percent air voids and percent passing 2.36-mm (no. 8) sieve (correlation coefficient of 0.4184). Although the last value appears high, the regression analysis, which will be discussed later, did not suggest the elimination of any of the dependent variables used.

The analysis continued by running a simple regression analysis of the coefficient of permeability as a dependent variable against each independent variable separately. Each factor was included in a simple regression and in a polynomial regression of second and third degrees. The square root, the exponent, and the log of each factor were also tested. Table 5 shows R^2 values for all different forms of the independent variables. The table shows no R^2 value higher than 0.45 was reached, which meant that *k* could not be accurately estimated by using just one variable.

The next step in the analysis was to run a multiple regression using different combinations of the independent variables. A

TABLE 4 Correlation Analysis Results

	PrcntAC	PrcntAIR	Pass8
PrcntAC		-0.1388	-0.0453
PrcntAIR	-0.1388		0.4184
Pass8	-0.0453	0.4184	

TABLE 5 R^2 Values for Simple Regression

variable	X	X^2	X^3	e^x	logx	$X^{0.5}$
prcntAIR	0.11	0.18	0.25	0.02	0.13	0.12
prcntAC	0.06	0.17	0.26	-	0.05	0.05
pass16	0.28	0.29	0.29	0.08	0.16	0.27
pass8	0.40	0.43	0.44	0.06	0.42	0.42
pass4	0.35	0.39	0.41	0.02	0.38	0.37

few nonlinear formulas were also tested but the analyses were mainly conducted using linear forms. The multiple regression computer runs showed that combining some of the independent variables in a linear form gave R^2 values higher than the summation of the R^2 values of the simple regression run on each variable separately. An example of this type of run combined percent air voids and percent passing the 1.18-mm (no. 16) sieve in a linear multiple regression, which gave an R^2 of 0.63. The simple regression had given R^2 values of 0.11 and 0.28 for percent air voids and percent passing the 1.18-mm (no. 16) sieve, respectively.

The following multiple regression equation gave the highest R^2 values:

$$k = 852.298 - 248.665 \times \text{prcntAC} + 97.507 \times \text{prcntAIR} - 95.521 * \text{pass8} \ (R^2 = 0.873)$$

where

k = coefficient of permeability in feet per day. (The associated values shown in the tables as cm/sec can be obtained by dividing this foot per day value by 2,835)
pass8 = percent by weight passing 2.36-mm (no. 8) sieve.
prcntAC = percent asphalt cement by total weight of sample.
prcntAIR = percent air voids by total volume of sample.

The R^2 value of 0.873 indicates that the equation is doing a good job of predicting permeability. Table 6 shows both measured and predicted permeability values using the equation. It indicates that the equation can be successfully used in estimating lab permeability values for asphalt-treated bases, especially in the range of 0.25–0.70 cm/sec (700–2,000 ft/day), where the coefficient of permeability is desired. Figure 5 shows a plot of predicted versus measured values of coefficients of permeability. Both Table 6 and Figure 5 indicate that the equation is less accurate in estimating permeability below 0.2 cm/sec (500 ft/day).

The next step was to study the residuals which are the difference between the measured and the predicted coefficients of permeability. First, all the residuals and the studentized residuals were calculated. The studentized residual is the difference between the fitted line and an observation in terms of standard deviation. Then a table of the unusual residuals and their corresponding studentized residuals was prepared. The unusual residuals are the ones that have studentized values higher than 2.0 or less than −2.0. It would be expected that about 5 percent of the residuals are unusual

TABLE 6 Actual and Predicted Permeability Values Using the Three-Term Regression Equation

Test No.	Actual Value	Pred. Value	Test No.	Actual Value	Pred. Value	Test No.	Actual Value	Pred. Value
1	610	758	21	914	1118	41	353	625
2	560	666	22	836	1029	42	1009	1042
3	672	623	23	990	871	43	515	627
4	650	657	24	1016	1124	44	581	716
5	955	769	25	984	1167	45	603	675
6	557	348	26	1526	1571	46	1525	984
7	491	273	27	1185	1189	47	579	854
8	126	-142	28	1369	1436	48	945	955
9	695	341	29	1372	1287	49	723	1084
10	600	243	30	1059	1179	50	877	1439
11	2096	2136	31	190	375	51	2165	1729
12	3480	2361	32	247	370	52	1897	1640
13	2363	2432	33	331	454	53	1752	1728
14	2281	2179	34	254	64	54	1880	1693
15	2300	2216	35	296	359	55	2352	1770
16	2023	2124	36	583	1185	56	1460	1327
17	1702	1709	37	855	1238	57	1418	1464
18	1894	1836	38	642	1051	58	1994	1627
19	2012	2085	39	1366	1273	59	1287	1248
20	1933	1876	40	1139	939	60	1515	1459

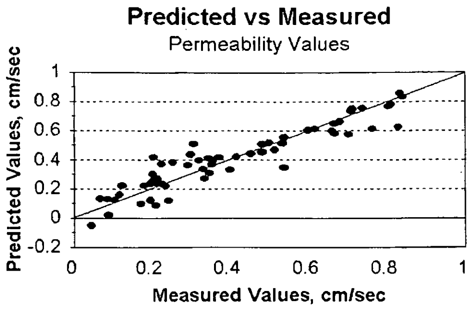


FIGURE 5 Predicted values versus measured values of the coefficient of permeability.

ones. Table 7 shows a list of the unusual residuals. Only four unusual residuals were observed (6.6 percent of the total residuals). No absolute studentized residual that is higher than 3.0 was observed.

The four points were then taken out of the database and the regression analysis was rerun. The rerun shows an improvement of 3.5 percent for R^2 (a new R^2 of 91.8 percent). A new table of the new unusual residual was prepared (Table 8). It shows a list of four unusual residuals, which have studentized values in the range of −2.35 to 2.51. These four points used to have lower values in the first analysis. However, their values went up in the new analysis due to the loss in the degrees of freedom (deleting four observation from the original database).

The influential points of the regression were also studied using a statistic called "leverage." The influential point is defined as a point that has a large influence on the fitted line. First, the average leverage of single data point was calculated as 0.066667. An influential point should have greater than 2.5 times the leverage of an average data point (*17*). The analysis indicated no influential points in either the first or the second run. Therefore, based on the facts mentioned above, the researchers conclude the regression equation mentioned before will be good for estimating the coefficient of permeability.

SUMMARY AND BENEFITS

The research produced a regression equation which can be used to predict permeability of asphalt-treated bases. The regression equation was based on 38-mm (1.5-in.) top size aggregates and 2–3 percent asphalt stabilization. Most highway agencies use these values in their design of asphalt-treated drainage layers, so the results of this research can be used to estimate the lab permeability of these layers. That ability will allow designers to more quickly select the percent asphalt and aggregate gradation for their desired application. These results can also be used to estimate the coefficient of permeability of existing asphalt-treated permeable layers. The equation is not suitable for dense-graded bases because only open gradations were tested in the research.

ACKNOWLEDGMENT

The authors would like to thank the Research Division of Vulcan Materials Company for providing the aggregates used in the research. Special thanks go to Dr. Chuck Marek and former Research Engineer Sandra Wood.

TABLE 7 Unusual Residuals (First Run)

Row	Permeability	Predicted Perm.	Residual	Studentized Residual
36	583	1185.92	-602.923	-2.72
46	1525	984.973	540.027	2.41
50	877	1439.71	-562.709	-2.57
55	2352	1770.33	581.673	2.64

TABLE 8 Unusual Residuals (Second Run)

Row	Permeability	Predicted Perm	Residual	Studentized Residual
36	855	1245.46	-390.458	-2.17
37	642	1062.45	-420.468	-2..35
48	2165	1722.16	442.8843	2.51
54	194	1615.6	378.402	2.10

REFERENCES

1. Cook, M., and S. Dynkins, P. E. Treated Permeable Base Offers Drainage, Stability. *Roads and Bridges*, May, 1991.
2. Ridgeway, H. H. Pavement Subsurface Drainage Systems. *National Cooperative Highway Research Program 96*, Transportation Research Board, November, 1982.
3. Flen, L. Open Graded Bases May Lengthen Pavement Life. *Roads and Bridges*, September, 1991.
4. Magidzadeh, K., and R. Elmitiny. *Development and Implementation of Pavement Drainage Design Guidelines in Ohio*. Ohio Department of Transportation and FHWA, U.S. Department of Transportation, 1982.
5. Magidzadeh, K. *Evaluation of Pavement Subsurface Drainage Conditions in Ohio*. Ohio Department of Transportation and FWHA, U.S. Department of Transportation, 1979.
6. Forsyth, R. A., J. B. Hannon, and W. C. Gray. *Performance of Two Layer Asphalt Stabilized Drainage Blanket for Highway Subdrainage*. California Department of Transportation, Translab No. 632618, FHWA No. D-2-1, June 1974.
7. Smith, T., R. Forsyth, and W. Gray. *Performance of an Asphalt Treated Drainage Blanket in a Flexible Pavement Section*. California Department of Transportation, Interim Report, January 1970.
8. Baldwin, J. S. Use of Open-Graded, Free Draining Layers in Pavement Systems: A National Synthesis Report. In *Transportation Research Record*, TRB, National Research Council, Washington, D.C., 1990.
9. Foryth, R. A. *Asphalt-Treated Permeable Material—Its Evaluation and Application*. National Asphalt Pavement Association, 1990.
10. Poul, H. R. *Evaluation of Asphalt-Treated Drainage Blanket in a Rigid Pavement Section*. Louisiana Department of Transportation Research Project No. 72-8B(B), U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-LA-78-117, January 1978.
11. Cedergren, H. R. *Drainage of Highway and Airfield Pavements*. John Wiley & Sons, New York, 1977.
12. Moulton, L. K. *Highway Subsurface Drainage*. Federal Highway Administration, Report No. FHWA-TS-80-224, August 1980.
13. Barber, E. S., and C. L. Sawyer. Highway Subdrainage. *Public Roads*, Vol. 26, No. 12, 1952, pp. 251–268.
14. Highlands, K. L., and G. Hoffman. *Subbase Permeability and Pavement Performance*. Pennsylvania Department of Transportation, Research Project No. 79-3, Final Report, 1987.
15. Yemington, E. G. *A Low-Head Permeameter for Testing Granular Materials*. ASTM Special Technical Report No. 163, 1963.
16. Mottola, V. Design and Implementation of Internal Roadway Drainage. Presented at Conference on Crushed Stone for Road and Street Construction and Reconstruction, Arlington, Va., June 14–15.
17. The Asphalt Institute. *Mix Design Methods for Asphalt Concrete MS-2*, 1990.

Publication of this paper sponsored by Committee on Subsurface Drainage.