

Permeability, Void Content, and Durability of Bituminous Concrete

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● ONE principle governing the design of bituminous concrete mixtures that is universally accepted is the inclusion of some criterion for durability. This may be expressed or implied; that is, there may be a specification for a maximum allowable void content in the mixture, the mixture may have been designed by some method which includes a voids criterion in the selection of the design asphalt content, or through experience the user may consider that the asphalt content must be held above some minimum in order to produce a durable mixture.

Closely related to the question of void content would seem to be the permeability of the mixture because, after all, the agents which cause the deterioration of the mixture must enter and occupy the void spaces in order to be effective. One might even hypothesize that permeability is a better measure of durability than simply a determination of void content because permeability measures the capacity of the porous medium to transmit fluid while the usual measure of voids in a bituminous mixture says nothing about their availability to the forces producing disintegration. At least one author has suggested that a type of measure of permeability be used as a control test during the construction of bituminous concrete mixtures (1)¹. Others have pointed toward a need for the pavement to be able to "breathe" and yet to be relatively impermeable to water (2).

A search of the literature has failed to produce any fundamental information concerning the relationship of the factors of permeability, void content and the durability of bituminous concrete. The measures of permeability that have been reported were not in the usual terms of cm², darcys, or cm. per sec., so it is difficult to relate any published data on bituminous mixtures to data published on other materials.

Our organization, in connection with a re-

search project for the U. S. Air Force, was asked to measure the permeability of several dense-graded bituminous aggregate mixtures. Samples of the mixtures were furnished in the form of cores 4-inches in diameter and of various thicknesses. The design of the apparatus for this work and the experience gained in performing permeability tests formed the background for the present study.

DESIGN OF PERMEAMETER

Two measures of permeability are in common use, one of which is a restricted case of the other. In order to be certain of a common basis of understanding, the following is quoted from Wyckoff, et al (3)²:

"As the carrier of a homogeneous fluid in viscous motion a uniform porous medium may be completely described by a specification of its 'permeability'. This term permeability may be defined physically as the volume of a fluid of unit viscosity passing through in unit time, a unit cross section of the porous medium under the influence of a unit pressure gradient, or, as the macroscopic velocity of a particle of a unit viscosity fluid at a point in the medium at which the pressure gradient is unity.

"Defined in this way, the permeability of a porous medium is independent of the absolute pressure or velocities within the flow system, or of the nature of the fluid, and is characteristic only of the structure of the medium. However, it has physical meaning only if the flow is of a *viscous* rather than *turbulent* character . . ."

In dimensions, permeability corresponds to an area, carrying the dimensions (length)². Most seepage problems found in Civil Engineering deal with the flow of water in cases where the unit weight and viscosity of the water vary within fairly narrow limits. It has become customary, therefore, to use a factor

¹ Italic numbers in parentheses refer to the list of references.

² An excellent presentation of Darcy's Law and the measurement of the permeability of porous media appears in Chapter II, pp. 55-120 of Reference 4.

called the *coefficient of permeability* in dealing with these problems. The *coefficient of permeability* is related to the *permeability* as defined by the expression,

$$k = K \gamma / \mu \quad (1)$$

in which K = permeability (cm²)

γ = unit weight of the fluid (gm/cm³)

μ = viscosity of the fluid (gm-sec/cm²)

k = coefficient of permeability cm./sec.

From this equation it is evident that k , the coefficient of permeability, is not a constant as it depends not only upon the properties of the porous material but also upon the properties of the fluid. The value of K , however, is *independent* of the properties of the fluid.

In designing a permeameter to measure K for bituminous mixtures, one first has to decide between a conventional water permeameter (either constant head or falling head) and a gas permeameter. Reference to the literature on the subject (3, 4, 5) indicated that the use of a gas provided a great many advantages, the most appealing of which was the ease of attaining measurable flows without the use of excessive pressures. The writers were uninformed as to the magnitude of the permeability of a dense-graded bituminous concrete but it was felt (and this feeling received support from the limited amount of literature on the subject) that the permeability of such a material must be extremely low and hence it would be difficult to force a measurable quantity of fluid through the samples. Since K is independent of the properties of the fluid used in its measurement and may be converted to k related to any fluid through a knowledge of the density and viscosity of the fluid in question, it is advantageous to measure K using a gas. It was decided, therefore, to design a permeameter in which the fluid used would be dry air and, if possible, make independent measurements with water to check the validity of the apparatus.

The principle of a laboratory determination of K using a gas is seen from the following equation which follows from Darcy's law and the definition of permeability (3, 4)

$$K = \frac{\mu \bar{Q} L}{A(P_1 - P_2)} \quad (2)$$

where K = permeability (cm²)

μ = viscosity of the gas (gm-cm/sec²)

\bar{Q} = volume of gas passing through specimen in unit time measured at the *mean* pressure (cm³/sec)

L = length of specimen or flow path (cm)

A = area of specimen or flow path (cm²)

P_1 = pressure at top of specimen (gm/cm²)

P_2 = pressure at bottom of specimen (gm/cm²)

The apparatus first devised is shown in Figure 1. On the assumption that even with the use of a gas, high pressures would be needed to force a measurable quantity of the fluid through the specimen, this apparatus was made capable of subjecting the specimen to a pressure of 3000 mm of mercury; hence the mercury well and the extremely long leg on the outflow pressure manometer. In making a permeability determination, the bituminous concrete core was sealed in the sample holder by pouring hot asphalt cement into the opening between the specimen and the wall of the holder. This insured that the only flow path for a fluid would be through the specimen. After the asphalt cement had cooled, the cover plates were bolted on and the holder was connected to the rest of the assembly. Air was then admitted and when a steady state of flow was reached readings were taken on the differential manometer, the outflow pressure manometer, and on the flow meter. These data plus air temperature, barometric pressure, and the dimensions of the specimen were sufficient to compute the permeability.

Experience has served to modify some of the details of this first design, but essentially it is the same as shown in Figure 1. Figure 2 shows the present form of the apparatus. Glass tubing has given way to copper tubing and the manometers are more compact. The flow meter is easily detached for cases where the quantity of air is too low for measurement

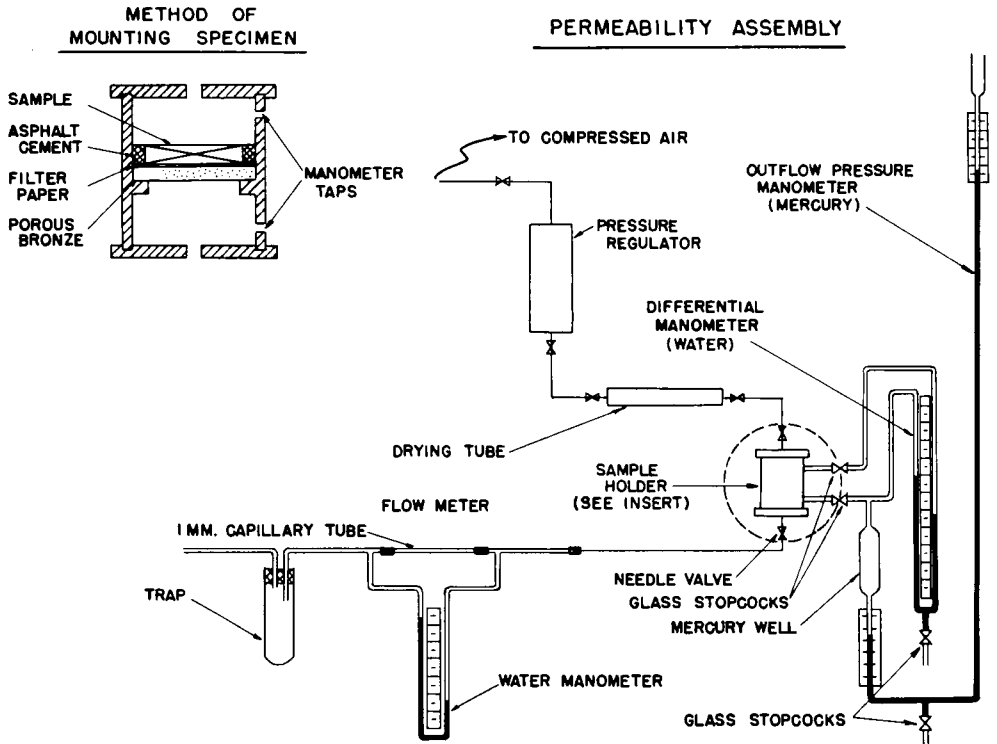


Figure 1.

with the flow meter and must be collected over water.

Early experience with this apparatus showed that the extremely high pressures were not necessary and that it would be feasible to check the air determinations against water determinations. Consequently a water permeability apparatus was devised which would accept the sample holder used in the air determinations. Six specimens were tested first by using air and then by using water. In these cases, after the air permeability test was completed, the sample holder was removed from the air apparatus, the manometer taps were capped, and the holder was connected to the water assembly shown in Figure 3. In this apparatus a usual falling head type test was made in which precautions were taken to exclude air from the system (13). From the data collected, values of K were computed. Table 1 shows a comparison of the results obtained with the air and water permeameters. These data were considered to represent sufficient verification, and all further tests were conducted in the air apparatus.

OUTLINE OF PRESENT INVESTIGATION

The present investigation has two major parts. In the first, a fundamental study of the permeability of sand-asphalt mixtures was attempted in order to bring out the basic relationships among asphalt content, void content, void size, and permeability. Sand-asphalt mixtures having one-size gradings or gradings containing only a few fractions were selected in order to approach an ideal pore system formed by the packing of uniform spheres. Table 2 shows the gradings used in this phase of the study. The sand is a local natural material.

These gradings were combined with various amounts of 60-70 penetration asphalt and formed into 4-inch diameter specimens. Compactive effort (double-plunger type) was included as a variable for some gradings. The porosities of the specimens were computed and the air permeabilities measured.

The second part of the study consisted of a comparison of the permeability and durability of bituminous concrete. An aggregate grada-

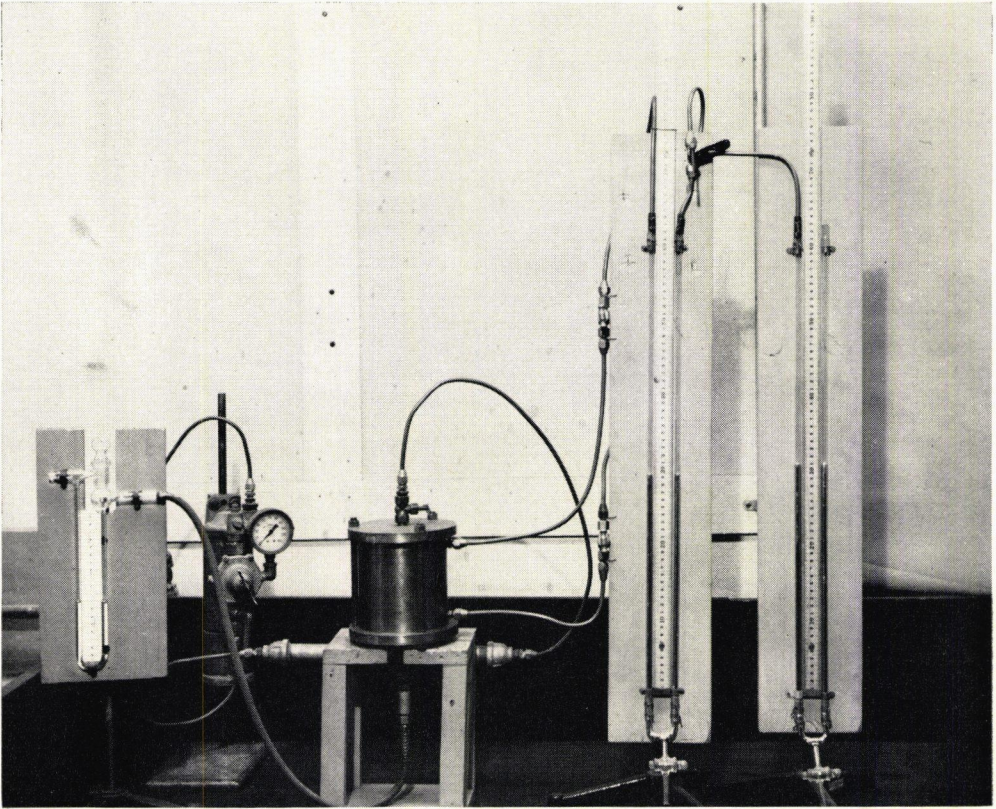


Figure 2. Present form of permeability apparatus.

tion meeting the specifications of the State Highway Department of Indiana and one conforming closely to the specifications of the U. S. Corps of Engineers, both for surface-course mixtures with $\frac{1}{2}$ -inch maximum aggregate size, were combined with various amounts of 60–70 penetration asphalt and formed into both beam specimens and cylindrical specimens. These gradings represent two basically different types of bituminous concrete. The sieve analysis for each type of mixture is listed in Table 3. The coarse aggregate fraction (material retained on the No. 8 sieve) was a crushed limestone and the fine aggregate was the same local natural sand used for the sand-asphalt specimens. The material passing the No. 200 sieve was limestone dust.

The Corps of Engineers grading was combined with 4, 5, and 6 percent asphalt (specification limits are 5–8 percent) and the Indiana grading with 5, 6, and 7 percent asphalt (spec-

ification limits are 6.5–8.5 percent). Three different compactive efforts were used in preparing these specimens in order to produce variations in void content and permeability. The beam specimens were made first and their void contents determined. The cylindrical specimens were made to match the beams in void content, this being accomplished by using double-plunger compaction and compacting to a predetermined volume. This system succeeded in producing specimens containing within 0.2 percent voids of the desired void content.

The cylindrical specimens were tested in the air permeameter and the beam specimens were subjected to alternate freezing and thawing³. The deterioration of the beams was checked periodically by determination of their sonic modulus of elasticity. This determination was made at 40°F (melting-ice bath) using

³ The deterioration cycle was to freeze in air at -20° F for 16 hours, thaw in water at 68° F for 8 hours.

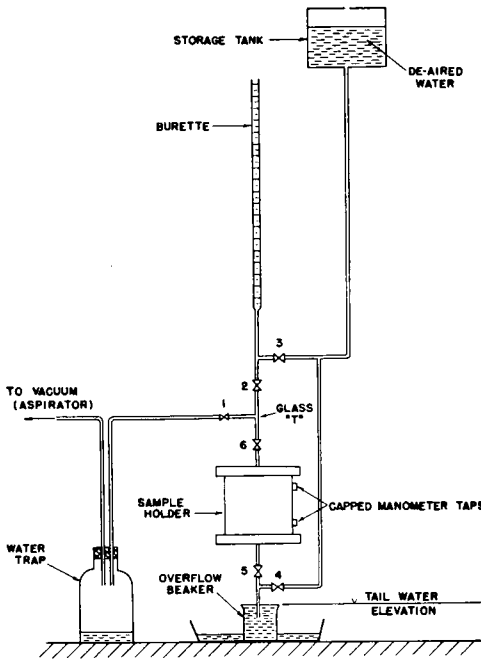


Figure 3. Falling head permeometer.

TABLE 1
COMPARISON OF AIR AND WATER PERMEAMETERS

Spec. No.	Permeability-cm ² Air Determination	Permeability-cm ² Water Determination
1	7.9×10^{-9}	7.5×10^{-9}
2	5.1×10^{-9}	5.1×10^{-9}
3	8.7×10^{-9}	9.9×10^{-9}
4	3.0×10^{-9}	3.4×10^{-9}
5	1.0×10^{-10}	1.0×10^{-10}
6	7.3×10^{-9}	7.5×10^{-9}

TABLE 2
SAND GRADINGS

Sieve		Percent by Weight				
		Grading				
Passing	Retained	A	B	C	D	E
# 8	# 16	100	50	100	50	25
# 16	# 50					
# 50	# 100		50		50	25
# 100	# 200					25

conventional sonic-testing equipment. The point of transverse resonant frequency was found by observing the trace on a cathode ray oscilloscope and checking the nodal points

TABLE 3
SIEVE ANALYSES OF BITUMINOUS CONCRETE MIXTURES

Sieve		Percent by Weight	
Passing	Retained	Indiana grading	C. of E. grading
1/2"	3/8"	9	14
3/8"	# 4	30	23
# 4	# 8	12	11
# 8	# 16	16	14
# 16	# 50	21	18
# 50	# 100	6	5
# 100	# 200	3	5
# 200	—	3	10
		100	100

(6, 7). A Poisson's ratio of 0.4 was assumed for all mixtures and further, it was assumed that this remained constant for the duration of the tests. That this assumption is not met is known from data collected in connection with a research investigation of the feasibility of the sonic method of test applied to bituminous mixtures. It may be said, however, that this fact does not invalidate the test method for following the deterioration of bituminous concrete (8).

RESULTS

All of the pertinent results have been summarized and tabulated in Tables 4 and 5. The Appendix contains a sample permeability and pore diameter calculation for the interested reader. In this section, the results are presented in graphical form in order to aid the discussion. In considering these results, it is well to keep in mind that the approximate conversion factor to change from permeability (*K*) to coefficient of permeability (*k*) for water at normal temperatures is 10^5 . That is, $K \times 10^5 = k$ water.

Tests on Sand-Asphalt Mixtures

Relationships between permeability and void content developed for soils and other materials indicate that a plot of void content versus log permeability for bituminous-aggregate mixtures should be linear (9). Consequently, the present results are expressed in this fashion.

Figure 4 is a plot of percent total voids versus log permeability in which the results of all of the tests on the sand-asphalt mixtures are shown. In general, the trend is linear, an increase in void content resulting in an in-

TABLE 4
RESULTS OF TESTS ON SAND ASPHALT MIXTURES

1	2	3	4	5	6	7	8	9
Grading	% Asphalt by wt. Agg.	Compaction*	Unit Wt. Mix	Est. Pore Diam.†	Permeability	% Total Voids	% Voids in Aggregate	% Agg. Voids Filled
			<i>lb. per ft³</i>	<i>microns</i>	<i>cm²</i>			
A	6	Normal	113.1	100	2.5 × 10 ⁻⁷	25.2	35.6	29.2
A	7	Low	113.3	100	2.5 × 10 ⁻⁷	24.8	36.6	32.2
A	7	Normal	116.4	90	2.3 × 10 ⁻⁷	22.7	34.9	34.9
A	7	High	118.4	80	1.8 × 10 ⁻⁷	21.4	33.8	36.6
A	8	Normal	114.7	90	2.5 × 10 ⁻⁷	23.0	36.6	37.1
A	9	Normal	115.1	90	2.1 × 10 ⁻⁷	21.5	36.8	41.5
B	7	Normal	115.0	50	1.1 × 10 ⁻⁷	23.7	35.8	33.7
B	8	Normal	117.0	40	6.7 × 10 ⁻⁸	21.4	35.3	39.3
B	10	Normal	118.1	40	1.8 × 10 ⁻⁸	18.7	35.9	47.9
B	12	Normal	120.3	30	1.1 × 10 ⁻⁸	15.1	35.8	57.8
C	10	Normal	109.6	40	6.0 × 10 ⁻⁸	24.6	40.5	39.2
C	12	Normal	112.3	30	2.9 × 10 ⁻⁸	20.9	40.1	47.8
D	6	Normal	118.4	140	2.3 × 10 ⁻⁷	22.6	33.4	32.3
D	8	Normal	121.4	100	1.3 × 10 ⁻⁷	18.2	32.7	44.3
D	10	Normal	123.1	80	2.2 × 10 ⁻⁸	15.1	33.1	54.3
D	10	High	126.2	70	1.0 × 10 ⁻⁸	13.0	31.4	58.5
E	6	Normal	121.2	40	4.2 × 10 ⁻⁸	20.8	31.8	34.5
E	8	Normal	124.0	30	2.3 × 10 ⁻⁸	16.6	31.3	46.9
E	8	Low	120.0	30	4.4 × 10 ⁻⁸	19.3	33.6	42.5
E	8	Int	123.6	30	1.5 × 10 ⁻⁸	16.9	31.6	46.5
E	8	High	125.2	20	2.0 × 10 ⁻⁹	15.8	30.7	48.5
E	10	Normal	126.2	20	8.4 × 10 ⁻⁹	13.0	31.4	58.5
E	10	Low	122.6	20	1.3 × 10 ⁻⁸	15.6	33.5	53.4
E	10	High	128.7	20	1.0 × 10 ⁻⁹	11.4	30.1	62.1
E	12	Normal	128.7	10	1.0 × 10 ⁻⁹	9.2	31.3	70.6

* A compactive effort was arbitrarily selected as "Normal" and variations from this were made in order to obtain other densities.
† These figures are merely relative and should not be thought to represent precise determinations.

crease in permeability. However, for the range of mixtures shown in Figure 4, variations in permeability are affected by other factors. The total void content of a bituminous-aggregate mixture is obviously only a measure of volume and says nothing about the distribution of this volume throughout the mixture. The grading of the aggregate, the degree of compaction, the percentage of aggregate voids filled with asphalt, and the asphalt film thicknesses are all factors which affect not only the total amount of voids but also void size and number, their continuity, and the shape of the flow channels.

Looking at an individual grading from the group, the points which resulted from the tests of grading B illustrate the situation uncluttered by the extraneous variable of grading. The deviations of these points from a straight line relationship is much less than the scatter for the entire mass of data. Here we have four mixtures having essentially the same percentage of voids in the aggregate (upper plot in Figure 4) and asphalt contents of 7, 8, 10, and 12 percent increasing from right to left. This resulted in permeability values of from 10⁻⁷ cm² to 10⁻⁸ cm², indicating

TABLE 5
RESULTS OF TESTS ON BITUMINOUS CONCRETE

% Asphalt by Wt. Mix	Compaction*	% Total Voids	% Voids in Aggregate	Permeability, cm ²	Original E, Psi × 10 ⁻⁶	% Orig E after 60 cycles Freeze & Thaw
Indiana Grading						
5	High	7.2	18.6	9.0 × 10 ⁻¹⁰	3.2	70
5	Medium	8.2	19.6	1.6 × 10 ⁻⁹	3.3	70
5	Low	9.0	20.2	7.8 × 10 ⁻⁹	2.7	62
6	High	4.5	18.4	4.0 × 10 ⁻¹¹	3.5	75
6	Medium	5.0	19.3	3.5 × 10 ⁻¹⁰	3.6	74
6	Low	7.0	20.6	1.4 × 10 ⁻⁹	3.0	76
7	High	2.5	18.8	5.2 × 10 ⁻¹²	3.5	85
7	Medium	2.8	18.9	1.9 × 10 ⁻¹¹	3.4	85
7	Low	4.2	20.2	4.6 × 10 ⁻¹⁰	2.8	85
Corps of Eng. Grading						
4	High	4.8	14.5	1.5 × 10 ⁻¹¹	4.0	76
4	Medium	7.0	16.4	2.0 × 10 ⁻¹¹	3.3	65
4	Low	8.0	17.2	4.7 × 10 ⁻¹¹	3.2	41
5	High	2.9	14.0	1.0 × 10 ⁻¹²	4.2	78
5	Medium	5.5	17.3	4.8 × 10 ⁻¹²	3.5	69
5	Low	7.3	18.9	3.1 × 10 ⁻¹¹	2.8	57
6	High	2.0	16.4	1.7 × 10 ⁻¹⁴	4.0	80
6	Medium	2.8	17.1	7.5 × 10 ⁻¹³	3.9	78
6	Low	4.0	18.1	4.4 × 10 ⁻¹²	3.4	79

* Impact compaction of the Marshall type. The method of preparing beams for sonic testing is described in reference 7.

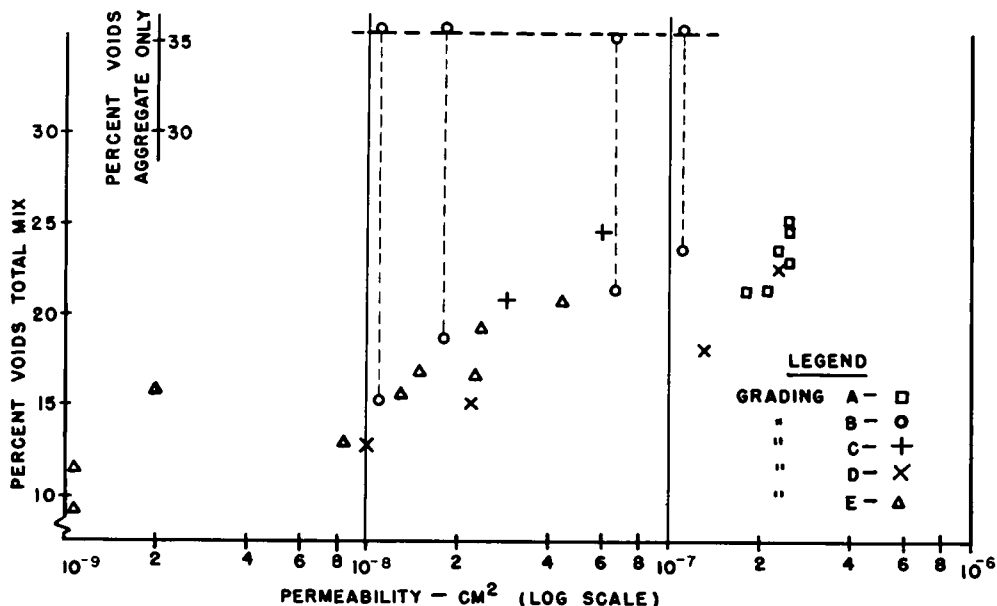


Figure 4. General relationships between voids and permeability for sand-asphalt mixtures.

a progressive filling of the voids in the aggregate framework and a reduction of the cross-sectional area available to flow.

When grading is variable, one may compare a specimen of grading A with one of grading B, each having about 36 percent voids in the aggregate. The grading A specimen has a permeability of 2.5×10^{-7} cm² and the grading B specimens a permeability of 1.8×10^{-8} cm². When the constant factor is percent total voids, one may compare a specimen of grading A having 25 percent total voids and a permeability of 2.5×10^{-7} cm² to a specimen of grading C also having 25 percent total voids but a permeability of 6.0×10^{-8} cm².

These cases illustrate that, except for the somewhat special case of constant voids in the aggregate and variable total voids, permeability is not a simple function of void volume, either total voids or voids in the aggregate. Obviously, pore size as well as total pore volume must be considered, and to give this factor quantitative meaning an estimate of pore diameter was made for these mixtures using a relationship involving the hydraulic radius of the pores. This in turn was estimated from the porosity and specific surface of the mixture (10)⁴, the results being shown in

⁴ This is explained and illustrated in appendix.

column 5 of Table 4. Although these numbers carry the units of microns, it cannot be emphasized too strongly that they are the result of very approximate calculations involving many simplifying assumptions. They do serve as indications of relative pore size and, in general, pore diameter decreases to the left in Figure 4.

Taking the specific examples already mentioned for the case of constant grading and percentage of voids in the aggregate but variable asphalt content and total void content, the decrease in permeability from 10^{-7} cm² to 10^{-8} cm² is accompanied by a reduction in pore diameter from 50μ to 30μ . For variable grading with constant voids in the aggregate (gradings A and B with 36 percent voids in the aggregate), the specimen having a permeability of 2.5×10^{-7} cm² has an estimated mean pore diameter of 100μ and that having a permeability of 1.8×10^{-8} cm² has an estimated mean pore diameter of 40μ . The last case, that of fixed total void content, the specimen of grading A having a permeability of 2.5×10^{-7} cm² had a mean pore diameter of 100μ compared to the specimen of grading C having a permeability of 6.0×10^{-8} cm² and a mean pore diameter of 40μ .

Finally, an attempt to illustrate the inter-

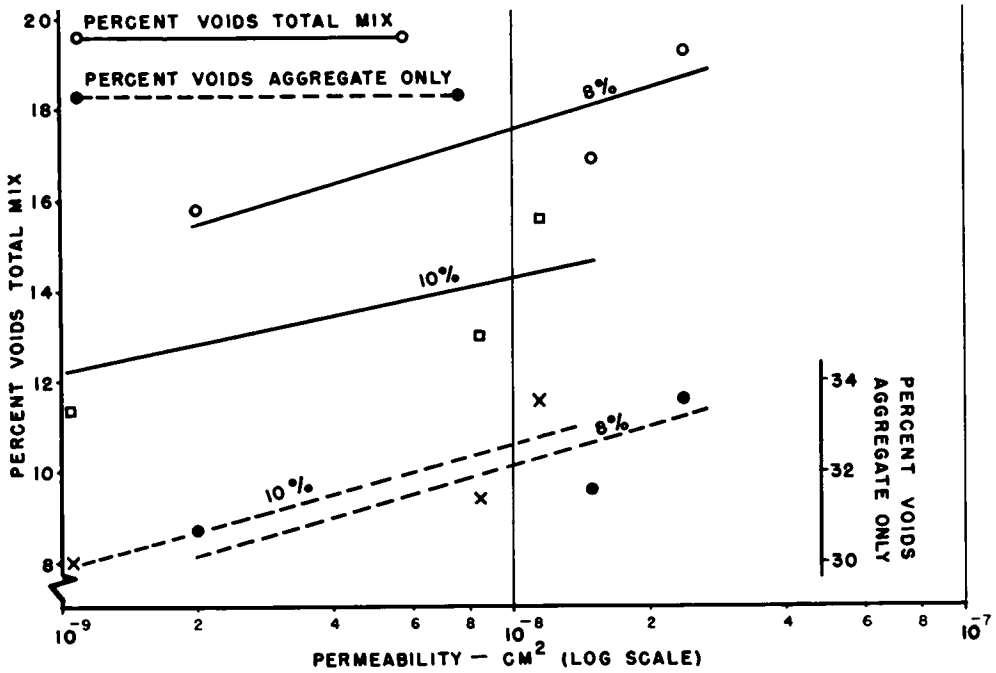


Figure 5. Permeability-voids relationships, sand-asphalt—grading E.

action among asphalt content, total voids, voids in the aggregate, and permeability is presented in Figure 5. Compactive effort was varied for grading E at 8 and 10 percent asphalt. At each of these asphalt contents, three specimens of different density were produced. In Figure 5, percent total voids and percent voids in the aggregate are plotted against permeability for these six conditions. Although the data presented are limited and a definite relationship is by no means established, it is apparent that the total voids curve for 8 percent asphalt lies well above that for 10 percent asphalt. This would indicate that for a given grading and value of percent total voids, the mixture having the lesser asphalt content would be less permeable. Or, from another standpoint, for a given grading, any particular permeability is achieved at a higher value of total void content for the specimen containing the lesser amount of asphalt. This is apparently contradictory, but a consideration of the other factors influencing permeability may explain the apparent anomaly. For any particular grading of aggregate mixed with varying quantities of asphalt, equivalent values of percent total voids can be achieved

only by variations in the degree of compaction. While this procedure will equalize total void contents, it will give the mixture containing the least quantity of asphalt the densest aggregate framework or the smallest percentage of "voids in the aggregate only". One might expect, from the relationships previously pointed out, that if for a given grading and value of total voids the mixture containing a lesser quantity of asphalt is less permeable than a similar mixture with more asphalt, the aggregate voids in the former would be less than in the latter. This is brought out by the relationship between voids in the aggregate and permeability also plotted in Figure 5. Here one sees that the curve for the mixtures containing 10 percent asphalt lies above that for 8 percent, indicating that for an equivalent aggregate framework, adding asphalt reduces permeability. Returning to the upper lines of the figure, at an essentially constant value of percent total voids (15.6 to 15.8) the mixture containing 8 percent asphalt was found to have a permeability of 2.0×10^{-9} cm² and the one containing 10 percent asphalt a permeability of 1.3×10^{-8} cm². However, the 10 percent specimen had a less-dense aggregate frame-

work than did the specimen containing 8 percent asphalt as evidenced by 33.5 versus 30.7 percent voids in the aggregate.

Tests on Bituminous Concrete

An inspection of Table 5 (Appendix) shows that large differences in permeability were observed not only between mixtures of the same grading at different asphalt contents, but even more so between mixtures of the two types of gradings included in this study. The permeability of most of the Indiana mixtures lay between 10^{-8} and 10^{-11} cm² but the more densely-graded Corps of Engineers mixtures had permeability values starting at 4.7×10^{-11} cm² and going as low as 1.7×10^{-14} cm². This latter value corresponds to a coefficient of water permeability, *k*, of approximately 10^{-9} cm per sec which Casagrande and Fadum term "practically impervious" (11).

Plots of percent voids in the total mix and percent voids in the aggregate versus permeability are shown in Figure 6 for the Indiana mixtures and in Figure 7 for the Corps of Engineers mixtures. The relationships discussed with respect to Figure 5 are again visible in Figure 6 and to a lesser extent in

Figure 7. Comparing the curves for 6 and 7 percent asphalt in Figure 6, a given permeability is achieved at a higher void content for the specimen containing the lesser amount of asphalt. On the other hand, and the point is perhaps better illustrated in this figure than in Figure 5, reference to the curves for voids in the aggregate shows that the 6 percent specimen must be compacted into a denser aggregate framework than the 7 percent specimen to achieve equal permeability. In a practical situation, this may not be easily accomplished.

Comparison between Figures 6 and 7 makes it apparent that grading of the mixture serves to place any relationship of voids and permeability on different levels; the relationship between voids and permeability is much different for the Indiana mixtures than for the Corps of Engineers mixtures.

The laboratory estimate of freeze-thaw durability, percent original modulus, is plotted against percent voids in the mix in Figure 8. *A priori*, for a given asphalt content one might expect percent original modulus to decrease with an increase in the void content of the mixture and further, that at a higher asphalt content, this decrease would occur less sharply.

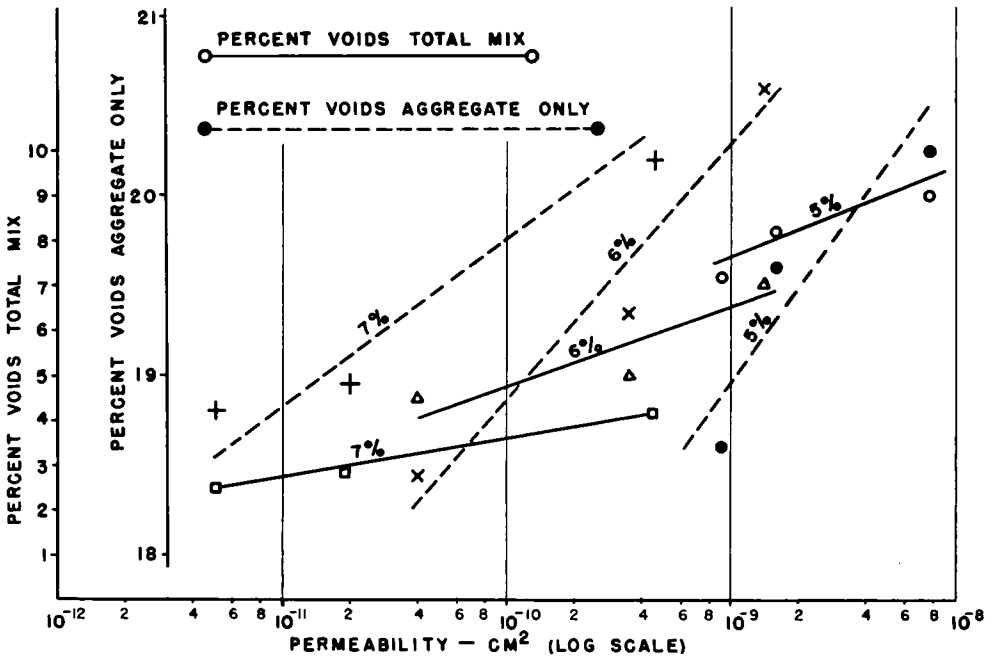


Figure 6. Permeability-voids relationships for Indiana mixtures.

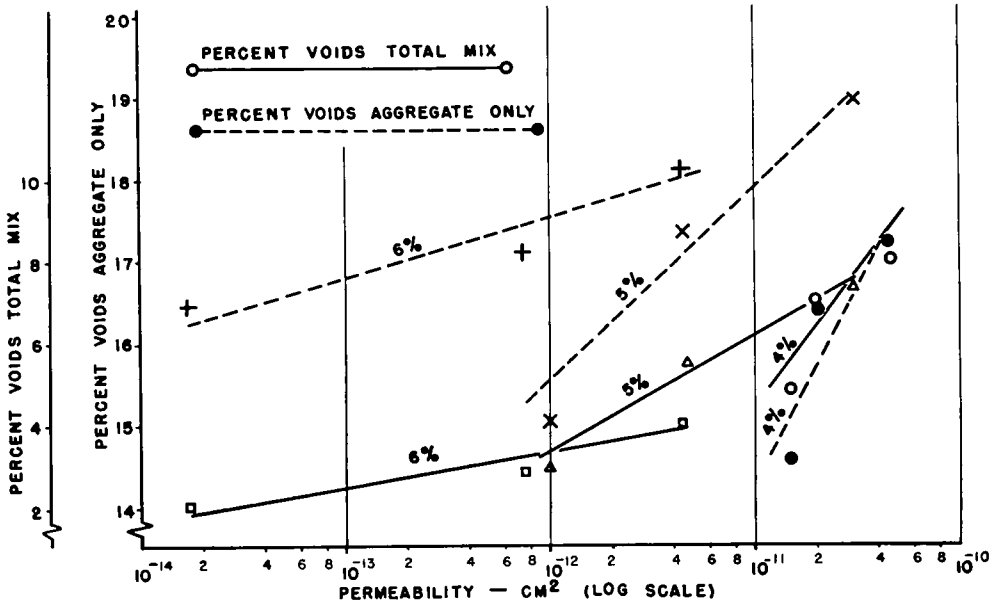


Figure 7. Permeability-voids relationships for C. of E. mixtures.

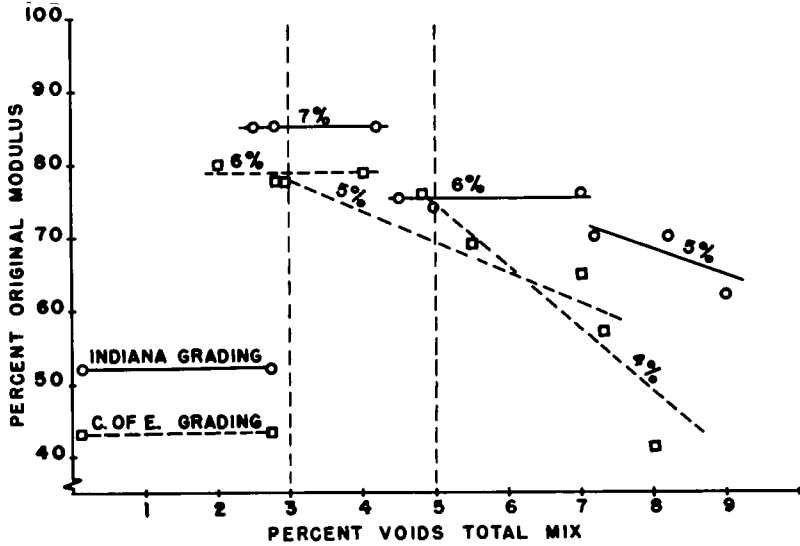


Figure 8. Relationships among voids, asphalt content, and loss in sonic modulus.

One might even postulate the existence of an optimum asphalt content from a durability standpoint at which compactive effort would be least critical, where an increase in voids within reasonable limits would not cause much of a change in durability. For the two cases shown in Figure 8, one, the mixtures of the

Corps of Engineers type, follows this general pattern, but the values for mixtures using the Indiana grading are relatively insensitive to void content except at the lowest asphalt content. Also, at the high void contents, it can be observed that the percent loss in sonic modulus is higher for the denser grading.

Using Hveem's table of surface area equivalents (12), the Indiana grading is found to have a surface area of approximately 20 sq. ft. per pound of aggregate. For the Corps of Engineers grading, the figure is 36 sq. ft. per pound. This illustrates the difference in asphalt film thickness existing between the two mixtures and perhaps serves to explain why the denser and less permeable mixture exhibits a sharper decrease in percent original sonic modulus under freeze-thaw treatment with increase in void content.

Permeability, too, has its role in these relationships but a plot of percent original modulus versus permeability would be redundant. The relationship between voids and permeability has already been discussed. Generally, the more impermeable the mixture, the larger the percentage of its original modulus is retained, *within each grading*. However, the added factor of asphalt film thickness prohibits the application of this statement to the grading range covered by both types of bituminous concrete used.

Also, it can be seen from Figure 8 that the laboratory freeze-thaw durability was relatively independent of the permeability of the mixture at reasonable asphalt contents. Whether or not this concept could be extended to the practical situation is problematical. Reference to Figures 6 and 7 shows that the permeability is much more sensitive to changes in void content at a high asphalt content than it is at a low asphalt content. It is possible that some measure of durability other than loss in sonic modulus in laboratory freezing and thawing would also reflect this. Further, from the standpoint of "breathing", a minimum permeability might be considered necessary in which case the sensitivity of permeability to changes in void content would be of importance.

The vertical lines on Figure 8 delineate the region of 3 to 5 percent total voids, the values specified for Corps of Engineers surface course design. It would appear from these data that for either type of mixture batched at a reasonable asphalt content, a specification of 3 to 5 percent voids would select mixtures durable to the type of weathering used in these tests, but for the Indiana mixtures, the range appears to be too restrictive. For the Indiana mixture with 6 percent asphalt, equivalent durabilities were measured at values up to 7 percent voids. This implies that any specification for void content found to be satisfactory for a particu-

lar type of grading should be applied with caution to mixtures of any other grading. Mixtures of other gradings, by virtue of differences in the aggregate make-up and the asphalt film thicknesses, may require a greater or lesser range of voids allowable for equal durability.

SUMMARY

The important results of this study have been summarized in this section as an aid to the reader and for ready reference. In so doing, however, it is not the intent of the authors that the following enumerated statements be given the status of conclusions because of data limitations.

1. A permeameter which employs compressed air has been devised for measuring the permeability of bituminous-aggregate mixtures. The results of tests made with this permeameter have been found to be in agreement with tests made in a conventional falling-head water permeameter.

2. Two types of bituminous concrete surface-course mixtures were tested in the air permeameter. One, a dense-graded mixture of the Corps of Engineers type, had permeability values between 10^{-10} and 10^{-14} cm². The other, a gap-graded mixture of the type used in Indiana had permeability values between 10^{-8} and 10^{-12} cm².

3. A relationship between voids and permeability was found which agrees with previous work on soils and other materials. A plot of voids versus log permeability is essentially linear. For bituminous mixtures this relationship is influenced by such factors as the gradation of the aggregate, compaction, and the amount of asphalt in the mixture.

4. For a given aggregate grading, mixtures having varying amounts of asphalt but compacted to a constant value of voids in the aggregate exhibit a linear relationship between voids in the mixture and log permeability.

5. For a given aggregate grading, variable asphalt content, and constant compactive effort which results in varying aggregate densities, a particular permeability is achieved at a higher value of total void content for a specimen containing the lesser amount of asphalt. This results from the mixture containing the lesser quantity of asphalt having the denser aggregate framework.

6. The relationship between voids and per-

meability for bituminous concretes of the range investigated is influenced to a large degree by asphalt content. At higher asphalt contents permeability is much more sensitive to changes in void content than it is at lower asphalt contents.

7. There is no general relationship between permeability and durability as measured by percent loss in sonic modulus caused by laboratory freezing and thawing. Any relationship has to be considered in reference to a particular grading.

8. A densely-graded mixture is not necessarily the best from a durability standpoint. The factor of asphalt film thickness must be considered.

9. The sonic method of determining dynamic modulus of elasticity has application in the field of bituminous-aggregate mixtures as a non-destructive test useful in following progressive changes caused by laboratory freezing and thawing.

10. The indications from this study are strong enough to warrant further investigation of both the sonic method as a means of following, and the influence of permeability on, deterioration caused by other types of accelerated weathering in addition to the freezing and thawing used in this study.

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APPENDIX

I. Calculation of permeability

$$K = \frac{\mu \bar{Q} L}{A(P_1 - P_2)}$$

Data: Spec. length = 4.19 cm, area = 79.34 cm²
 Barometer: 748.5 mm Hg = 1018.0 gm/cm²
 Air temperature = 32°C

Measured flow = 10.40 cm³/sec at atmospheric pressure

Differential manometer reading = 128.5 mm H₂O

Outflow manometer reading = 10.0 mm Hg

$$\mu = 186.7 \text{ mp or } \frac{186.7 \times 10^6 \text{ gm - sec}}{980.7 \text{ cm}^2}$$

$$P_2 = \text{Outflow manometer reading plus atmospheric pressure} = (10.0 \times 1.36) + 1018.0 = 1031.6 \text{ gm/cm}^2$$

$$(P_1 - P_2) = \text{Differential manometer reading} = 128.5 \text{ mm H}_2\text{O} = 12.85 \text{ gm/cm}^2$$

$$\begin{aligned} \text{Flow at Mean Pressure} &= \frac{10.4 \times 1018.0}{1038.1} \\ &= 10.20 \text{ cm}^3/\text{sec} \end{aligned}$$

$$\begin{aligned} K &= \frac{186.7 \times 10^{-6}}{980.7} \times \frac{10.20 \times 4.10}{79.34 \times 12.85} \\ &= 7.8 \times 10^{-9} \text{ cm}^2 \end{aligned}$$

II. Calculation of pore diameter

Carmen (10) derives the following relationship for average pore size.

$$d = 4m = 4 \left[\frac{\epsilon}{(1 - \epsilon)S_0} \right]$$

m = hydraulic radius, the ratio of area of cross-section to perimeter of cross-section

ϵ = porosity

S_0 = specific surface—cm²/cm³

and

d = average pore diameter—cm

Specific surface values were approximated from a table of surface area equivalents given by Hveem (12).

For a typical case, a specimen of grading A has a porosity of 0.25 and a specific surface of 126.3 cm²/cm³.

$$d = 4 \left[\frac{\epsilon}{(1 - \epsilon)S_0} \right] = \frac{4 \times 0.25}{0.75 \times 126.3} = 0.010$$

or $d = 100\mu$

Significance of Variation as Related to Asphalt-Aggregate Mixes

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● IT is convenient to think of all matters related to the quality of a prepared asphalt-aggregate mix in terms of specification, production and inspection. Ordinarily if we comply with the requirements of these three terms, it may be stated that satisfactory control prevails. However, when specification or inspection requirements are not being met, this is evidence that the quality or the quality characteristics of the product has been subjected to a certain amount of variation, which may be due to 1. the result of change, or 2. assignable causes. Variation is an inherent fundamental characteristic of any manufactured product including asphalt-aggregate mixes. Therefore, it should be recognized, understood and applied by engineers concerned with either design or acceptance specifications.

Samples are taken for the primary purpose of predicting the quality of the remaining aggregation from which the sample was drawn. Let us assume that this aggregation of material varies in its physical properties, and this we can ordinarily prove by taking samples and testing until we obtain several test results that are different. Therefore, we must know something about the variability of the overall aggregation of material before we can make a valid prediction of its true test characteristic. Let us take an example of 100 Marshall briquets made up and tested for stability during the day's run on a hot mix plant. If the range of values obtained were divided into equal class intervals and a count made of the number of test results in each class interval, we would then be able to classify the results according to the frequency of the in-