supervisor, is acknowledged for scheduling and performing the many tests. And appreciation goes to S. A. Kelley, our computer programmer, for running the analysis program.

The contents of this report reflect my views, and I alone am responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policy of the U.S. Department of Transportation. The opinions, findings, and conclusions expressed in this paper are mine and not necessarily those of the sponsoring agencies.

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Laboratory Measurement of Permeability of Compacted Asphalt Mixtures

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An improved method for measuring the permeability of compacted asphalt mixtures in the laboratory was developed. It eliminates the difficulties encountered with using a rubber membrane for sealing the specimen in a metal cylinder. In the new method, the specimen wall is coated with a one-part silicone rubber sealer that is applied as a paste with a spatula and is permanently flexible and waterproof. After the coating has cured and been checked for leaks, a known pressure difference is created by a vacuum across the specimen. The rate of air flow through the specimen is obtained at various differential pressure values. Flow rate is plotted against pressure difference, and the slope of the straight line portion of the curve is calculated. Permeability is calculated by using this slope value and the specimen height. The technique measures the true permeability, eliminates the possibility of specimen deformation during testing and the problems associated with other methods, permits no asphalt contamination, and is versatile with respect to aggregate gradation and asphalt grade.

The importance of measuring permeability, the small openings in a medium that permit liquids or gasses to pass through it, has long been recognized in the field of asphalt concrete. In 1955 McLaughlin and Goetz (1) hypothesized that using permeability gives a better measure of durability than using void content alone. Permeability, in their opinion, can be used to measure the capacity of a porous medium to transmit fluid, whereas the normal measure using voids in a bituminous mixture does not directly measure the forces producing disintegration.

Hein and Schmidt (2), after conducting a study on air permeability of asphalt concrete, suggested that permeability measurements are essential to routine mix design studies. Their results indicated that the void content of mixtures is not necessarily proportional to permeability when the variation is caused by gradation.

An investigation to evaluate the effects of air permeability and air void content on the durability of asphalt concrete was conducted by Smith and Gotolski (3). One of their conclusions was that air permeability is a good indicator of the extent of accessibility of the air void system.

This literature review indicates a need for a laboratory permeability measuring technique for predicting asphalt concrete behavior from the standpoint of durability.

METHOD

Keyser and Gilbert (4) conducted a study of methods that were then (1973) being used to determine the permeability of bituminous mixtures. They reported that 15 types of permeameters were in use in North America and Europe, of which 9 could be used in the laboratory.

In general, air permeability is measured by creating a known pressure differential across a specimen and then measuring the amount of air flow over a known period of time. The test requires that the specimen be encased so that air flow is limited to passage through it. This has been accomplished by sealing the specimen in a metal cylinder with asphalt or other sealing material. This method, however, is destructive to the specimen; it is also difficult to be certain that a complete seal has been obtained.

Goode and Lufsey (5) used paraffin to prevent leakage of air between the sides of the specimen and the membrane. Before extracting the asphalt, they discarded the outer 0.64 cm (0.25 in) of the specimen with the intention of eliminating paraffin contamination of the extracted asphalt. Even then, they found enough contamination to invalidate their results.

Another procedure is to place the specimen in a cylindrical rubber membrane fastened to a hollow metal cylinder with hose clamps (Figure 1). The membrane is then inflated enough to prevent air from passing between the walls of the specimen and the membrane during the permeability measurement. Macroscopically the procedure seems to be sound, but, when the surface-membrane contact is observed microscopically (Figure 1B), the following points can be noted.

1. The membrane is in contact with only the high points of the aggregates (for example, points a, b, c, d, and e in Figure 1). Thus, air passing between the specimen surface and the membrane would give a permeability value higher than it really is.
2. The gradation of the mix plays an important role. For coarse mixes, specimen-membrane contact will be reduced, which may also result in a deviation from the true permeability value.
3. Inflation pressure in the membrane is important. If the pressure is low, there will be less specimen-membrane contact. If the pressure is too high, the specimen may deform, especially if it is of low density or the binder is of low viscosity.
4. The thickness of the membrane is important. A thick membrane will also result in less specimen-membrane contact. If the membrane is too thin, it will bulge near the hose clamps and increase the probability of bursting.

Figure 1. Permeability measurement of compacted asphalt mixtures using rubber membrane.

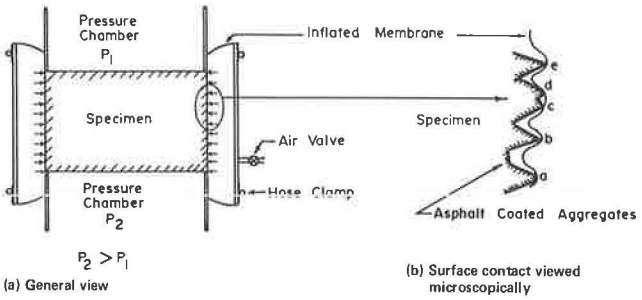
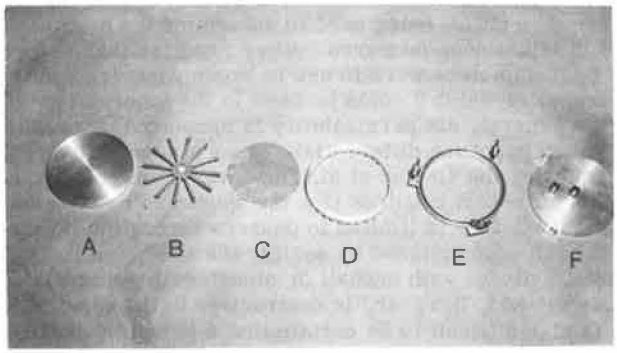


Figure 2. Component parts of the mold assembly: (A) base plate, (B) specimen supporter, (C) wire gauze, (D) lower collar, (E) upper collar with "o" ring, and (F) cover plate.



The above points clearly indicate that it is difficult for the experimenter to visualize the extent of the specimen-membrane contact area. As described earlier, the amount of air flow through the specimen is measured at a certain pressure differential across it, which in turn is used to calculate the permeability of the compacted bituminous mixture. Theoretically, the true permeability value of this compacted mixture should be obtained from the total amount of air flowing through each channel in the specimen. In the above procedure, total air flow is measured as the sum of air flowing through each channel plus the amount flowing between the specimen wall and the membrane. Therefore, one will get a permeability value higher than the true value if air passes between the specimen wall and the membrane.

In general, the greater the specimen surface-membrane contact area, the closer the results will be to the true permeability value. Because the extent of the contact area relies on so many factors, especially when coarse mixes are used, it may be rather difficult to obtain the true value of permeability.

TECHNIQUE AND MEASUREMENT PROCEDURE

The present method eliminates the above problems. The idea is to replace the membrane with a rubber coating enveloping the specimen. This procedure for measuring the permeability of asphalt concrete is outlined as follows.

Apparatus

Equipment includes a mold assembly for the 10.16-cm (4-in) diameter specimen (Figures 2, 3, and 4) (suitable modifications should be made for specimens of other sizes), a vacuum pump, flowmeters (range for air, 1 to 77 000 ml/min), a manometer, a pressure line, silicone rubber sealer (6), and a thermometer.

Specimen Preparation

Limestone aggregate and 200-250 penetration asphalt were used in this study. The aggregates, brought from the quarry, were dried and sieved, then washed and dried again. Each specimen was batched by component factions in accordance with the cumulative batch weight formula.

Each individual batch of aggregates was thoroughly mixed and heated to 149 ± 3°C (300 ± 5°F), and the asphalt was heated separately to 135 ± 3°C (275 ± 5°F). The two were mixed in an electric mixer (Hobart model N-50) for 2 min. The batch was then ready for compaction. The gyratory testing machine was used as a compaction device because it provides a good simulation of field compaction (7).

Procedure

1. The specimen supporter is set on the base plate. If the mix is very coarse and has low density, a fine wire mesh may be placed on the specimen supporter to eliminate the chance of being unsupported between the ribs (Figure 2). The lower collar is placed on the base plate. The lower assembly is now ready to receive the specimen for coating (Figure 5).
2. The specimen is placed on the supporter and coated with the silicone rubber sealer all around, leaving only about 2.5 cm (1 in) from the top of the specimen (Figure 6). One should make sure that enough sealer is

applied at the top of the lower collar so that it adheres to the specimen.

3. After the sealer has partially cured (approximately 8 h), the specimen (the lower collar will be fixed to it) is lifted, the upper collar is placed upside down on the base plate, and the specimen is reversed and seated on the supporter. The whole assembly should be elevated so that the upper collar sits properly on the base plate. The rest of the specimen is coated with the same sealer, and adheres to the upper collar (Figure 7). The assembly is then left overnight for the sealer to cure.

4. The next day, the specimen is turned upside down and placed on the supporter. The cover plate is seated on the upper collar and the wing nuts tightened (Figure 8).

5. In checking for leaks, one of the two openings in the cover plate is closed, and pressure is applied gradually through the other. Then the entire assembly is immersed in water and pressure slightly higher than the maximum anticipated suction pressure to be applied during the permeability measurement is applied (Figure 9). Air will start bubbling through the semicircular holes in the lower collar (Figure 10). The sides of the specimen should be checked for any air leaks. If any leak is observed, it should be repaired and rechecked.

6. The height of the specimen (H) is measured (Figure 11).

7. The specimen is now ready for testing. One opening of the coverplate is connected to the flowmeter, through which air is to be drawn by a vacuum pump. The other opening is connected to the manometer to record the pressure differential created across the specimen (Figure 12).

8. The rate of air flow (R) in millileters per minute through the specimen is shown by the flowmeter at various pressure differential values (ΔP), by using a control valve in the vacuum line.

9. The test temperature is recorded.

10. The rate of airflow (Y axis) versus pressure difference (X axis) is plotted, and the slope (S) of the straight line portion of the curve using a linear regression equation is obtained (8). By using this slope value and specimen height, the permeability can easily be calculated.

Figure 3. Exploded view of mold assembly.

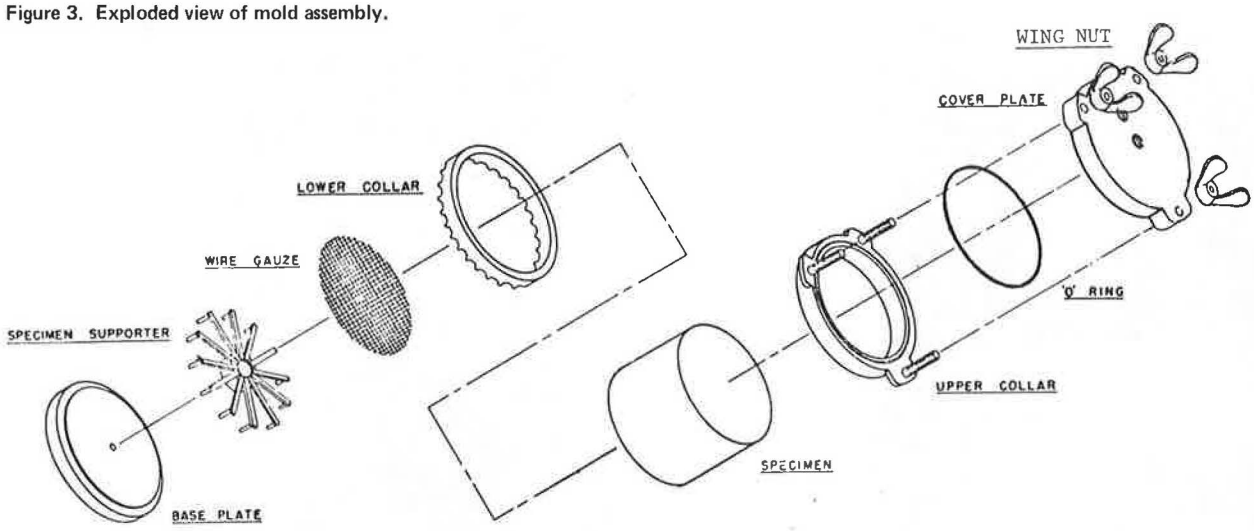


Figure 4. Detailed view of mold assembly.

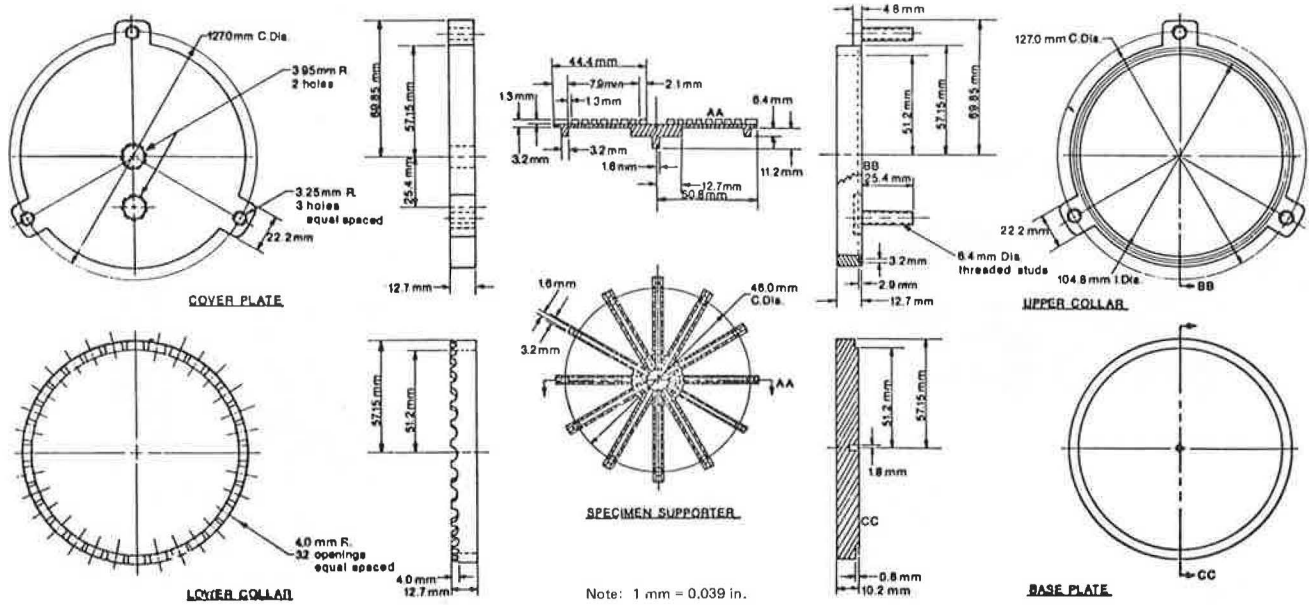


Figure 5. Lower assembly ready to receive specimen for coating.

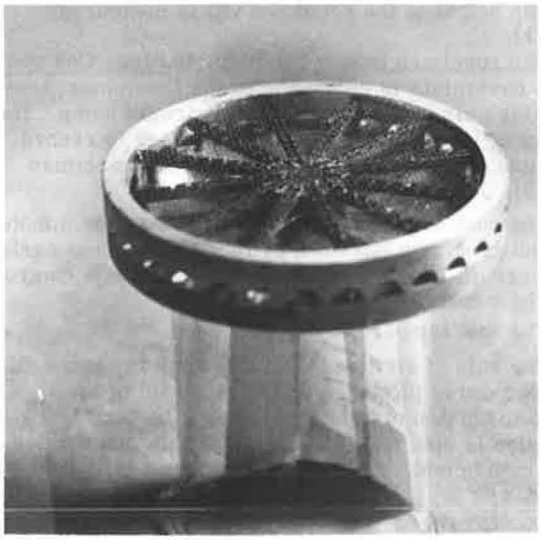


Figure 6. Specimen coated to within 2.5 cm (1 in) of top.

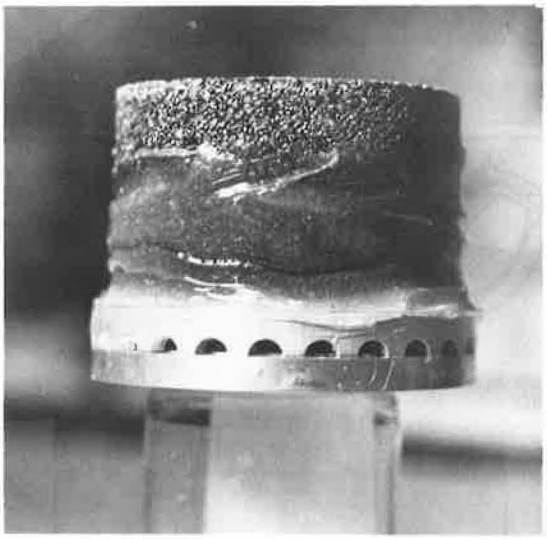


Figure 7. Completely coated specimen.

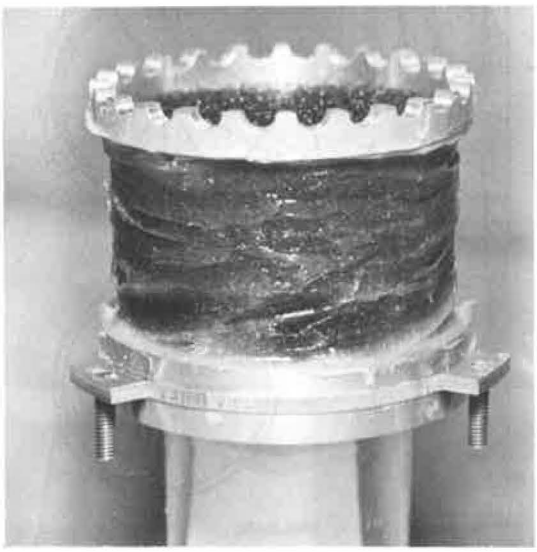


Figure 8. Assembly ready for leak check.

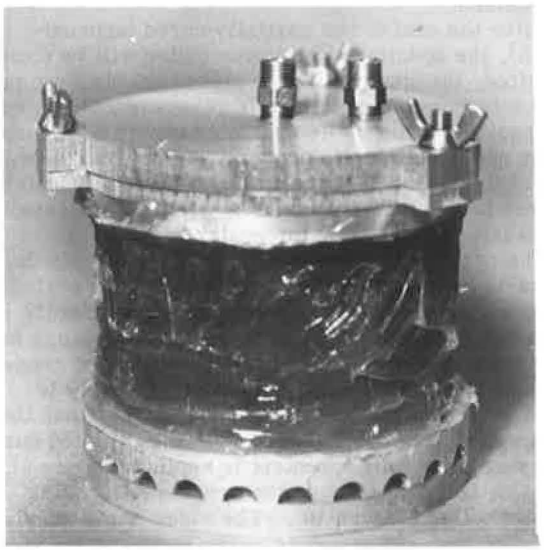
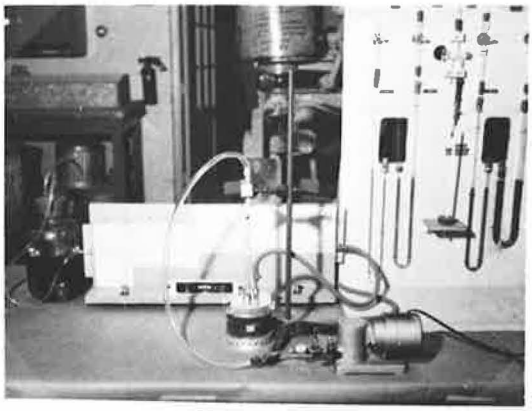


Figure 9. Air leak check set-up.

Figure 10. Air bubbling through openings in lower collar.

Figure 11. Measuring height of specimen.

Figure 12. Measuring permeability of specimen.



Calculations

The data for four combinations of varying asphalt content, aggregate gradation (Table 1), and compactive effort (8) are presented here in order to demonstrate the technique and its versatility. Values for the various variables involved in mix preparation, compaction, and the properties of the compacted mixes are given in Table 2. Table 3 presents values for rate of flow versus pressure difference across the specimen for various mixtures. These values are plotted in Figures 13, 14, 15, and 16.

The slopes of the straight line portions of the curves were obtained by linear regression (8) and are given in Table 3. The slope and specimen height values were then substituted into the following permeability formula.

$$K = 3.812 \times 10^{-11} \times S \times H \quad (1)$$

Table 1. Gradation of the mixes.

	Percentage Passing			
	Single Size Mix		Graded Mix	
U.S. Sieve Size	A Coarse	B Fine	C[a] Coarse Side	D[a] Mid Point
12.5 mm			100	100
9.5 mm			80	88.5
4.75 mm	100		40	50.0
2.36 mm	0		30	39.0
1.18 mm			18	26.5
600 μm			9	16.5
300 μm		100	3	8.0
150 μm		0	0	0.0

Note: 1 mm = 0.039 in and 1 μm = 0.0039 in.
[a] Type B no. 11 (9).

Table 2. Preparation and properties of single size and graded mixes.

Item	A	B	C	D
Preparation				
Aggregate type	Limestone	Limestone	Limestone	Limestone
Asphalt grade, penetration	200 to 250	200 to 250	200 to 250	200 to 250
Percent asphalt by weight of aggregate	2	8	5.5	5.5
Gyratory settings				
Angle of gyration	1°	1°	1°	1°
Ram pressure, kPa	689.4	689.4	1378.8	689.4
Type of roller	Fixed	Fixed	Fixed	Fixed
No. of gyratory revolutions	12	25	32	19
Properties				
Specimen height, cm	6.31	6.01	6.32	5.85
Unit weight, kg/m^3	1675	1658	2117	2208
Percent air voids (total calculated)	33	30	7.6	11.1
Permeability, cm/s	2.94×10^{-5}	2.50×10^{-7}	5.52×10^{-9}	1.03×10^{-7}

Note: 1 kPa = 0.145 lbf/in^2; 1 cm = 0.39 in; 1 kg/m^3 = 0.062 lb/ft^3.

Table 3. Rate of air flow versus pressure difference across the specimen for single size and graded mixes.

A			B			C			D		
Pressure Difference (cm of water)	Slope[a]	Rate of Air Flow (ml/min)	Pressure Difference (cm of water)	Slope[a]	Rate of Air Flow (ml/min)	Pressure Difference (cm of water)	Slope[a]	Rate of Air Flow (ml/min)	Pressure Difference (cm of water)	Slope[a]	Rate of Air Flow (ml/min)
0.010	308 482	895	1.27	2747	1200	3.81	58	32	2.54	1147	1810
0.020		2025	1.91		1950	5.08		60	3.81		2435
0.031		3230	2.54		2620	6.35		88	5.08		2935
0.041		4740	3.18		3500	7.62		120	6.35		3500
0.051		5790	3.81		3900	8.89		147	7.62		4140
0.061		7040	4.45		4700	10.16		178	8.89		4690
0.071		8215	5.08		5350				10.16		5105
									11.43		5450
									12.70		5590

Note: 1 cm = 0.394 in and 1 ml = 0.035 oz.
[a] Slope of the straight line portion of the curve in milliliters per minute per 25.4 mm.

Figure 13. Rate of air flow versus pressure difference across specimen A.

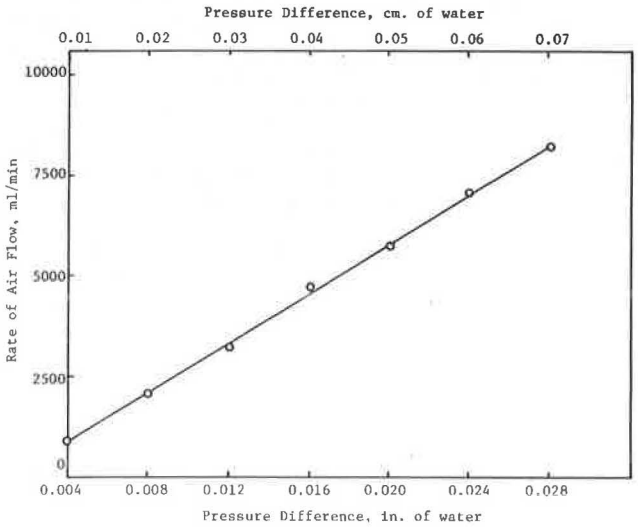
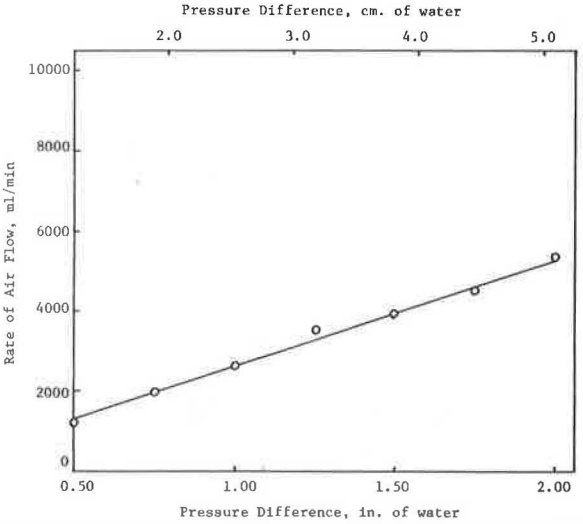


Figure 14. Rate of air flow versus pressure difference across specimen B.



where

K = permeability in centimeters per second,
S = slope of the straight line portion of the curve in millileters per minute per 25.4 mm, and
H = height of specimen, in centimeters.

The above formula is for a testing temperature of 20°C (68°F) and was modified from the conventional formula of permeability, given by Hein and Schmidt (2),

$$K = \mu \bar{Q} L / A(p_1 - p_2) \qquad (2)$$

where

μ = viscosity of air in poises,
$\bar{Q}$ = rate of air flow, in cubic centimeters per second,
L = height of specimen in centimeters,

Figure 15. Rate of air flow versus pressure difference across specimen C.

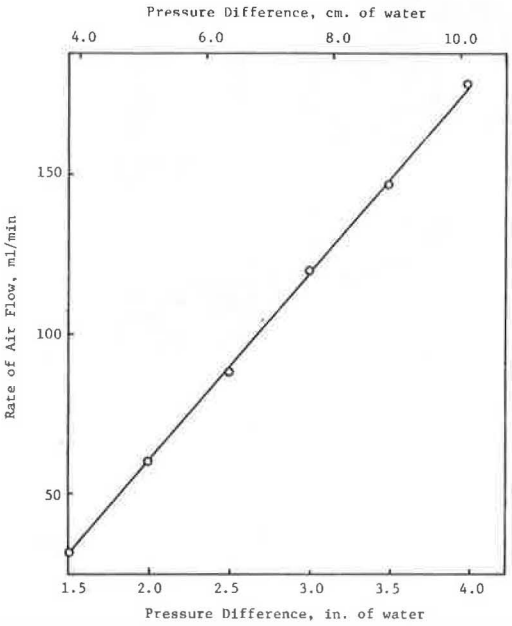
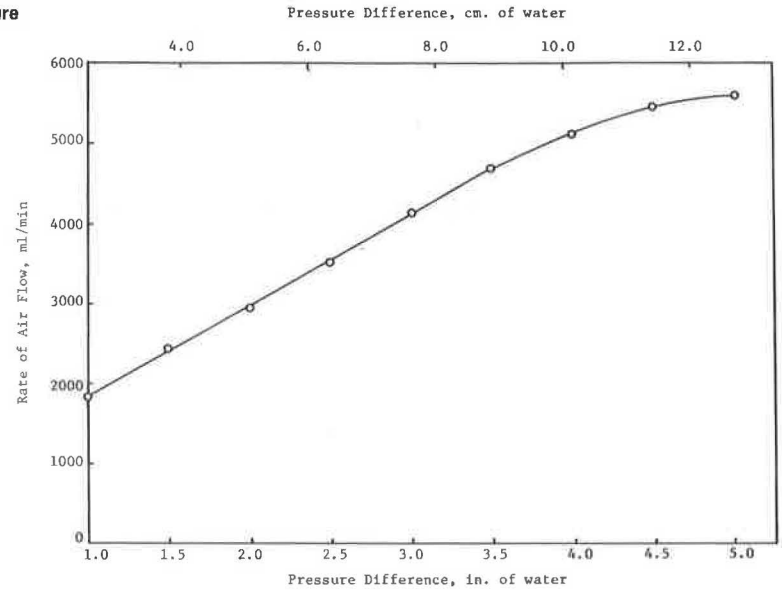


Figure 16. Rate of air flow versus pressure difference across specimen D.



A = cross-sectional area of specimen in square centimeters, and
$p_1 - p_2$ = pressure differential, dynes per square centimeter.

For specimens 10.16 cm (4 in) in diameter, a test temperature of 20°C (68°F), and a value for μ at 20°C (68°F) of 1.813×10^{-4} Pa·s (9), the above formula reduces to:

$$K = (3.812 \times 10^{-11} \times R \times H)/\Delta P \quad (3)$$

where

R = rate of airflow in milliliters per minute,
H = height of specimen in centimeters, and
ΔP = pressure differential in centimeters of water.

By using the slope of the straight line portion of the curve obtained from the plot of rate of airflow (R) (Y axis) versus pressure difference (ΔP) (X axis), this reduces to Equation 1.

For temperatures other than 20°C (68°F), the formula should be suitably modified as

$$K = 3.812 \times 10^{-11} \times S \times H \times (\mu \text{ @ test temperature}/1.813) \quad (4)$$

CONCLUSIONS

The major objective of this work was to develop a technique to measure the true permeability value of compacted asphalt mixtures. It eliminates such variables as selection of membrane thickness and selection of inflation pressure. Also, it avoids the possibility of specimen deformation.

The method has broad applicability; for example, the permeability value can be obtained for both very coarse and very fine single size mixtures (Figure 17) and for mixtures made with low viscosity asphalts, since coating arrests deformation.

Because the slope value of the plot between rate of air flow versus pressure difference across the specimen is used for permeability calculations, the need for adjusting the zero error is eliminated. The method also eliminates the possibility of using incorrect data in the turbulence range (11), because only the slope of the straight line portion of the curve is used in the calculations. It also eliminates asphalt contamination, because no silicone sticks to the specimen when the layer is peeled away (Figure 18).

The assembly prepared in this way for permeability measurement can be very effectively used for laboratory simulation of the weathering of asphalt due to air movements in the pavement.

Figure 17. Single size coarse and fine compacted mixtures.

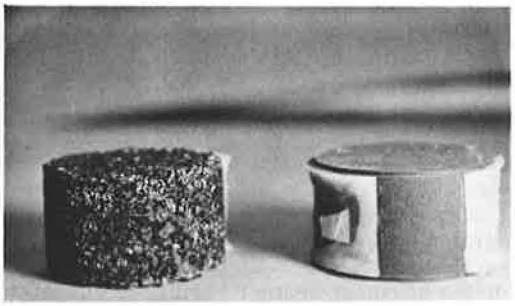
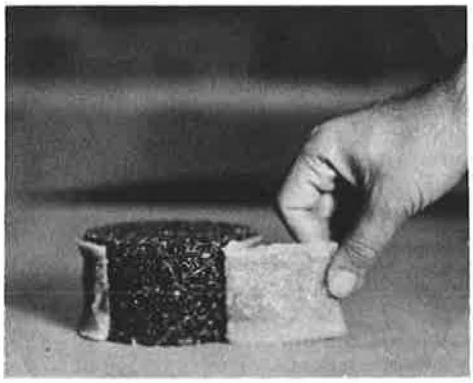


Figure 18. Easily removed coating shows no asphalt contamination.



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**Mr. Kumar was with Purdue University at the time this research was done.*