ASPHALT ABSORPTION AS RELATED TO PORE CHARACTERISTICS OF AGGREGATES

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Absorption of asphalt by aggregates is of paramount importance to account for the loss due to absorption because, in the design of densely graded bituminous concrete mixes, a relatively small variation in the asphalt content will result in mixtures that are too rich or too lean. Pore characteristics are the most important properties of the aggregates, especially in the absorption phenomenon. Most attempts have been made by the investigators to evaluate aggregate absorption without direct analysis of the pore characteristics. Review of literature on pore characteristics and methods of determination of asphalt absorption by aggregates are presented. Rock cores $\frac{1}{2}$ in. in diameter from six Iowa limestones, having variable absorptive characteristics, have been used throughout this study. Mercury porosimetry has been employed to evaluate total effective porosity, pore-size distribution, pore-volume distribution, and extent of "ink-bottle" pores. Asphalt absorption has been determined by the immersion method and the bulk-impregnated specific gravity method. A relation between pore parameters and asphalt absorption has been established by regression analysis. Pore size in the range of 0.1 to 0.05 μm seems to determine the amount of water absorption, whereas pore size in the range of 0.7 to 0.05 μm determines the asphalt absorption.

•ABSORPTION of asphalt by aggregates is recognized as an important factor in the design of mixes for bituminous pavements. For the calculation of the quantity of asphalt required for a particular aggregate, the surface capacity of an aggregate has to be taken into account. The surface capacity is composed of three factors: surface area, which varies with gradation; variation due to the roughness of the aggregates; and variation due to true effective porosity or absorption in the aggregates themselves (1). The last factor determines the quantity of asphalt actually present on the surface of the aggregate and available as binder. Obviously, where the asphalt or any of its important constituents (in selective absorption) are absorbed, the absorbed portion can no longer act as part of the binder proper. This may lead to the failure of the pavement because (a) the resulting thin film around the aggregate is more susceptible to stress and weathering (especially water action) and (b) low-temperature cracking may occur because of the change in the physical and chemical properties of asphalt film.

Thus, the evaluation of exact absorption of asphalt by aggregates is of paramount importance to account for the loss due to absorption because, in the design of densely graded bituminous concrete mixes, a relatively small variation in the asphalt content will result in mixtures that are dangerously rich or dangerously lean (2).

Some aggregates are rejected for highway construction purposes if the absorption of asphalt is substantial. Increased consumption and the continued demand for higher quality aggregates, because of accelerated highway construction programs and expanded usage of concrete in the building industry, are rapidly exhausting many suitable aggregate sources, which results in a shortage of quality aggregates available at reasonable cost in many areas of the country. Therefore, tests and criteria on absorptive capacity

of aggregates with respect to asphalt are needed to ensure high-quality paving mixtures and to ensure that so-called "marginal aggregates" are not rejected unjustifiably because of the lack of criteria.

The present work was undertaken to study the pore characteristics of six different aggregates and their absorptive capacity with respect to commonly used asphalts.

LITERATURE REVIEW

Aggregates may be considered as porous media (solid bodies containing pores) in the study of the process of absorption. Hence, the following review is divided into pore characteristics and asphalt absorption by aggregates as evaluated in the present study.

Pore Characteristics

The importance of pore size and pore-size distribution has been realized and studied extensively in the case of concrete aggregates. However, there have been no published data on the study of the pore-size characteristics of asphalt aggregates and their relationship to absorption other than that by Lee (3).

The pores in a porous system may or may not be interconnected. The interconnected part of the pore system is called the effective pore space of the porous medium.

The pores in rock are pictured as irregularly shaped cavities connected by capillaries that have varying shapes and diameters (4). The smallest entrance diameter to a pore is used as the measure of the size of that pore.

According to Scheidegger (5), the only unambiguous pore size should be the largest sphere that can be put into the space containing the point in question.

The pore characteristics that are generally determined are porosity, pore size, pore-size distribution, and a specific internal area called specific surface.

Porosity

Probably the most common method used in the casual investigation of aggregate porosity is to measure the absorption and assume that the volume of water absorbed equals the pore volume, i.e., to assume complete saturation. The result may be termed water-permeable or 24-hour soaked porosity. Dinkle (4) obtained vacuum-saturated porosity and reported good correlation among saturated porosity, 24-hour soaked porosity, and mercury intrusion porosity. The main point with respect to the absorption method as a measurement of porosity is that one rarely gets complete saturation (6).

Washburn and Bunting (7) employed a gas expansion method based on Boyle's law to determine porosity. Beeson (8) modified the apparatus, and most of the commercially available equipment is based on this principle.

Porosity can be determined visually on a polished or thin section of aggregate by measuring void area (pore space) microscopically by various camera-lucida or photomicrographic methods. Sweet (9) has used such optical methods on aggregates.

Dolch (10) determined the effective porosity of limestone aggregates with the McLeod gauge porosimeter as developed by Washburn and Bunting (11).

Pore Size and Specific Surface of the Solids

Brunauer, Emmett, and Teller (12) advanced BET theory for obtaining specific surfaces from sorption isotherms. Surface adsorption has also been used to obtain indirectly a curve for pore-size distribution.

Other methods (13, 14) for pore size and specific surface are small angle X-ray scattering, heat of immersion, rate of dissolution, ionic adsorption, and radioactive and electrical means; however, these have been little used.

The method (15) most frequently used is that of injection of mercury into the pore system. This method has been adopted in the present study. Washburn (16) was the first to suggest the use of pressed mercury in determining the pore-size distribution of porous solids (assuming the model is based on a system of circular capillaries).

The relation developed by him may be stated in the following form:

$$p(r) = -2\sigma \times \cos \theta \qquad (1)$$

where p is the pressure applied, r is the pore radius, σ is the surface tension of mercury, and θ is the contact angle of the mercury with respect to the solids.

Ritter and Drake (17) put Washburn's conception to practical use and developed the apparatus. The apparatus generally referred to as a mercury porosimeter has been described by Purcell (18). Subsequently, Drake (19) utilized a high-pressure mercury porosimeter and made measurements up to 60,000 psi to measure pore radii down to 20 Å. The method was applied successfully to concrete aggregates by Hiltrop and Lemish (20).

Determination of Percentage of Asphalt Absorption

Many investigators have attempted to evaluate aggregate absorption with kerosene and have applied suitable corrections for the amount of asphalt absorbed by aggregates in mixture design. Hveem (1) devised the Centrifuge Kerosene Equivalent (CKE) test in 1942. Lohn (21) and Donaldson et al. (22) proposed some modifications to the Hveem CKE test. Because kerosene has wetting properties similar to asphalt, it is believed to be a better representative absorption agent than is water (23). Oils have also been used by some investigators (1, 24) to evaluate the absorptive capacity of coarse aggregates.

In 1942, Goshorn and Williams (2) developed the immersion method in which the coarse aggregate is immersed in a tarred wire basket in asphalt at 275 F for 3 hours. Because the aggregate is in contact with an unlimited supply of asphalt at relatively low viscosity for extended periods of time, the absorption is much higher than would be expected in a bituminous mixture. However, the values can definitely be taken as the absorptive potentials of aggregates used for bituminous mixtures (25).

Rice (26) proposed a procedure to determine the maximum specific gravity of the mixture by using volumetric flasks. The absorption of asphalt by aggregate in a mixture can be calculated if the maximum specific gravity of the mixture (after Rice's method), the asphalt content, and the bulk specific gravity of the aggregate used in the mixture are known.

The U.S. Corps of Engineers (27, 28) developed and used the bulk-impregnated specific gravity method in the design and control of bituminous paving mixtures. It has also been used to determine the asphalt absorption by porous aggregates.

In this study, asphalt absorption of rock cores has been determined by using two methods: immersion method and bulk-impregnated specific gravity method.

INVESTIGATIONS

Materials

Six major limestone aggregates, having variable absorptive characteristics, have been studied.

In the present study, which also includes the pore characteristics of the aggregate, rock cores (½ in. in diameter) drilled from stone blocks received from the respective quarries were used. This was done to have consistent and comparable results in studying pore characteristics and asphalt absorption because of the following.

1. Rock cores taken from one stone block are more likely to be homogeneous and uniform, and correlation between absorption and pore characteristics can be more realistic.

2. Rock cores or cylinders allow uniform drying of surface for saturated surface dry condition in ASTM Test C 127-59 for determination of bulk specific gravity and thus give reproducible results to be used in the immersion and bulk-impregnated specific gravity methods for calculating asphalt absorption.

The source and designation of the aggregates (cores) studied are given in Table 1. Hereinafter, the cores shall be referred to in this study by name of quarry from which the stone blocks were received. Two asphalt cements have been included in this study. The properties of the two asphalts studied are given in Table 2.

Testing Procedure

Water-Permeable or 24-Hour Soaked Porosity—The water-permeable porosity was computed by multiplying the percentage of water absorption by the bulk specific gravity where both were determined on $\frac{1}{2}$-in. diameter rock cores from the standard 24-hour soaked procedure as per ASTM Test C 127-59.

Effective Porosity or Mercury-Intrusion Porosity—Effective porosity was determined with mercury capillary apparatus or mercury porosimeter apparatus. The effective pore volume was the volume of mercury injected into the rock core at a pressure of 2,000 psia. The bulk volume was that occupied by the rock surrounded by mercury at a pressure of 5 psia. In other words, the effective porosity, as defined in this study, is the ratio of the interconnected permeable pores in the pore-entry radius range, from 21.32 to 0.05 μm, to the total bulk volume of particle including pores, expressed as a percentage.

Pore Size and Pore-Size Distribution—The pore size and the pore-size distribution were determined by using a mercury porosimeter apparatus manufactured and distributed by Ruska Instrument Corporation, Houston, Texas, under license of the Shell Development Company. The apparatus and procedure have been described in detail elsewhere (3, 20). The data of the cumulative volume of pores or volume of mercury absorbed at various applied pressures or corresponding pore radii can be treated in various ways. The data in this study are as follows.

Nonnormalized Pore-Size Distribution Curve—The distribution curve represents the frequency of occurrence of one particular pore size. The curve indicates at what size (for example, r) the greatest number of pores occurs. Ritter and Drake (17) derived the equation for a nonnormalized distribution curve:

$$D(r) = p/r \times [d(Vo - V)dp] \qquad (2)$$

where

$D(r)$ = distribution function;
p = applied pressure, psia;
r = pore-entry radius, μm;
$Vo - V$ = volume of mercury injected from zero to pressure p, cc/gram; and
$d(Vo - V)/dp$ = slope of Vo - V versus pressure as determined from pressure-pore volume curve.

All the terms on the right side of Eq. 2 are known or determinable. Values of the derivation are readily obtained by graphical differentiation. Plotting $D(r)$ against r gives the distribution curve.

Porosity Distribution Curves—Curves of cumulative porosity versus pore radius were plotted for all rock cores. The cumulative porosity is the cumulative pore volume divided by total bulk volume of a particle.

Percentage of Porosity in Various Pore-Radius Ranges—The porosity for pores between certain radii is the ratio of the pore volume in these sizes to the total bulk volume of an aggregate including pores, expressed as a percentage. These porosities were determined for the following pore radius ranges in microns: 21 to 11, 21 to 5, 21 to 2, 21 to 1, 11 to 1, 5 to 1, 1 to 0.5, 1 to 0.1, 1 to 0.05, 0.1 to 0.05, and 0.7 to 0.05.

Hysteresis in Mercury Porosimetry—When the pressure is systematically released in the mercury porosimeter, the depressurization curve does not follow the original pressurization curve, and some of the mercury is retained in the sample even on complete removal of pressure. The phenomenon was also observed by Ritter and Drake (17), who attributed the action to the so-called "ink-bottle" shape of the pores. Curves illustrating hysteresis have been obtained for all rock cores.

Determination of Asphalt Absorption by Immersion Method

The method used is essentially that developed by Goshorn and Williams (2) for coarse aggregates, with the exception that the rock cores were immersed in asphalt at 300 F

(instead of 275 F) for 1 hour only (instead of a total of 3 hours). Also, the samples were not cooled at room temperature and reheated at 275 F before the cores were removed from the asphalt. It is felt that, by using this modification, (a) the time required to complete the test can be greatly reduced, (b) the conditions more nearly approach the field operation of hot mix, and (c) the absorption should be more indicative of the maximum or potential absorptive capacity of an aggregate (25).

Determination of Asphalt Absorption by Bulk-Impregnated Specific Gravity of Aggregates

The procedure used in determining the bulk-impregnated specific gravity is essentially that described by Ricketts et al. (28).

RESULTS AND DISCUSSION

Pore Properties

Water-Permeable or 24-Hour Soaked Porosity—Results of water-permeable or 24-hour soaked porosity, bulk specific gravity, and water absorption as determined from ASTM Test C 127-59 for $\frac{1}{2}$-in. rock cores are given in Table 3.

Effective Porosity or Mercury-Intrusion Porosity—Effective porosity covers the pore-entry radius from 21.32 to 0.05 μm. The results are given in Table 4.

Pore Size and Pore-Size Distribution—Plots were made from the data of the cumulative volume of pores or volume of mercury absorbed at various applied pressures or corresponding pore radii. From these, graphs were drawn after necessary computations.

Porosity Distribution Curves—Curves of cumulative porosity (percent) versus pore radius for rock cores are shown in Figure 1.

Nonnormalized Pore-Size Distribution Curves—The curves representing the frequency of occurrence of one particular pore size, as mentioned earlier, are shown in Figure 2.

Percentage of Porosity in Various Pore-Radius Ranges—The porosity for pores between certain radii was determined for the following pore-radius ranges in microns: 21 to 11, 21 to 5, 21 to 2, 21 to 1, 11 to 1, 5 to 1, 1 to 0.5, 1 to 0.1, 1 to 0.05, 0.1 to 0.05, and 0.7 to 0.05. The last range was included in the study based on six nonnormalized pore-size distribution curves that had a range of 0.05 to 0.7 μm for the most frequently occurring pore radius. The porosities are given in Table 4.

Statistical Analysis Results—Out of the various pore-size ranges, important ranges (which will be specified later) were selected. Linear correlation coefficients between these main pore properties were determined so as to study how they vary. The computed correlation coefficients are given in Table 5.

The pore-size ranges given in Table 5 were selected on the basis of their correlation with asphalt absorption. Those with poor or no correlation were not included. It appears that mercury-intrusion porosity is mainly dependent on the porosities in the following ranges of pore size: 0.7 to 0.05 μm, 1 to 0.05 μm, 1 to 0.1 μm, and 1 to 0.5 μm. The porosities in the following ranges have fair correlations with mercury-intrusion porosity and show a general trend: 5 to 1 μm, 11 to 1 μm, 21 to 2 μm, and 0.1 to 0.05 μm. Based on the determination of 24-hour soaked porosity and mercury-intrusion porosity, the following plots show good correlations.

24-Hour Soaked Porosity Versus Mercury-Intrusion Porosity—Correlation coefficient between methods is 0.7093. Menlo and Linwood cores behave similarly. Cook and Alden cores tend to absorb less water, whereas Keota and Pints cores absorb more water as compared to mercury intrusion.

Mercury-Intrusion Porosity Versus 0.7- to 0.05-μm Porosity Range—Because values of pore radius r corresponding to maximum value of D(r) in the nonnormalized pore-size distribution curves (Fig. 2) range from 0.05 to 0.7 μm, this range was correlated with mercury-intrusion porosity. The correlation coefficient is 0.9553 (Table 5). Porosity in the 1- to 0.05-μm range is the controlling factor for total mercury intrusion, whereas for water absorption the range is 0.1 to 0.05 μm. The correlation coefficient between this porosity and water absorption is 0.9782.

Table 1. Aggregates studied.

County	Quarry	Beds or Ledges	Geological Formation
Adair	Menlo	3 to 6 Argentine	Missourian series, Pennsylvanian system
Black Hawk	Pints	Rapid	Cedar Valley formation, Devonian system
Hardin	Alden	—	Gilmore City formation, Mississippian system
Scott	Linwood	Davenport	Devonian system
Story	Cook	—	St. Louis formation, Mississippian system
Washington	Keota	Beds 14 to 22	Osagian series, Mississippian system

Table 2. Properties of asphalts studied.

	Asphalt	
Property	A (85 to 100 penetration)	B (120 to 150 penetration)
Penetration, 77/100/5	92	127
Specific gravity	1.0077	1.0237
Flash point, F	600	605
Fire point, F	670	665
Softening point, F	120	118
Viscosity at 140 F, poises	1,144	727
Viscosity at 77 F, poises	3.95×10^6	1.58×10^6
Thin-film loss on heating 5 hours at 325 F, percent	0.10	0.08
Penetration of residue, 77/100/5	54	72
Percentage of original penetration (thin-film residue)	57.4	53.3
Soluble in CCl_4, percent	99.84	99.83
Ductility at 77 F, cm	130+	130+
Ductility at 77 F (thin-film residue), cm	130+	130+
Spot test	Negative	Negative

Table 3. Bulk specific gravity, water absorption, and porosity of rock cores.

Cores	Bulk Specific Gravity	Water Absorption (percent)	24-Hour Soaked Porosity (percent)
Menlo	2.637	0.90	2.37
Pints	2.271	7.22	16.40
Alden	2.510	1.72	4.32
Linwood	2.636	0.90	2.37
Cook	2.565	2.16	5.54
Keota	2.489	3.12	7.77

Table 4. Porosity in different pore-size ranges.

Pore-Size Range (μm)	Quarry (percent)					
	Menlo	Pints	Alden	Linwood	Cook	Keota
21 to 11	0.17	0.12	0.10	0.13	0.17	0.71
21 to 5	0.26	0.18	0.28	0.24	0.25	1.52
21 to 2	0.36	0.32	0.50	0.32	1.10	2.29
21 to 1	0.43	2.30	1.12	0.36	7.0	2.68
11 to 1	0.26	2.18	1.02	0.23	6.83	1.97
5 to 1	0.17	2.12	0.84	0.12	6.75	1.16
1 to 0.5	0.08	6.20	5.28	0.08	5.30	0.22
1 to 0.1	0.45	12.9	8.29	0.51	10.0	0.97
1 to 0.05	0.55	14.65	8.45	0.54	10.4	1.98
0.1 to 0.05	0.10	1.75	0.19	0.03	0.40	1.01
0.7 to 0.05	0.52	10.45	5.80	0.49	7.2	1.86
21 to 0.05[a]	0.98	16.88	9.60	0.90	17.44	4.66

[a] Mercury-intrusion porosity.

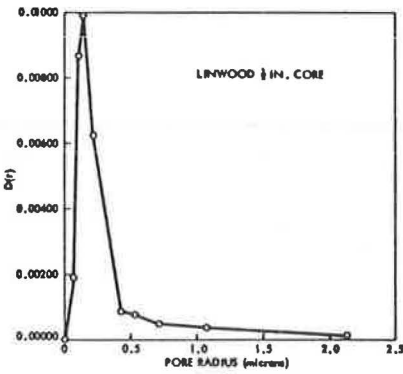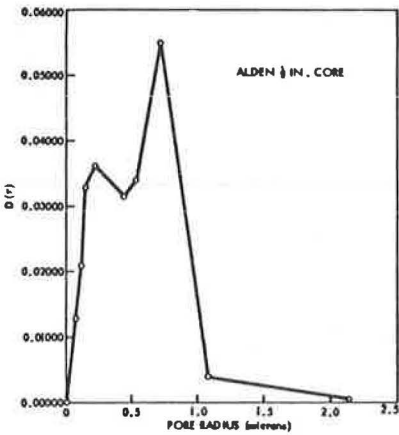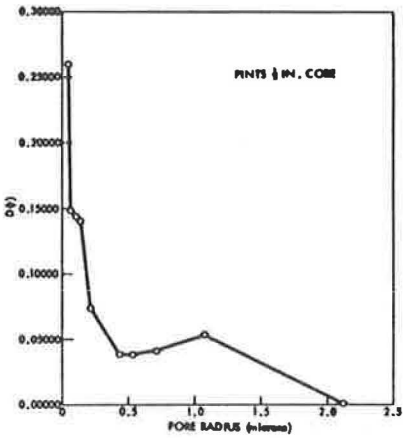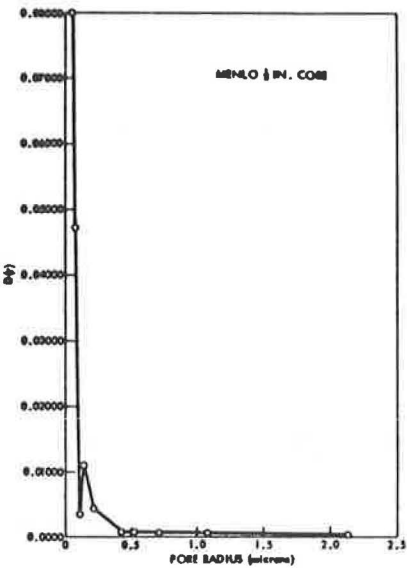**Figure 1. Cumulative porosity distribution.**
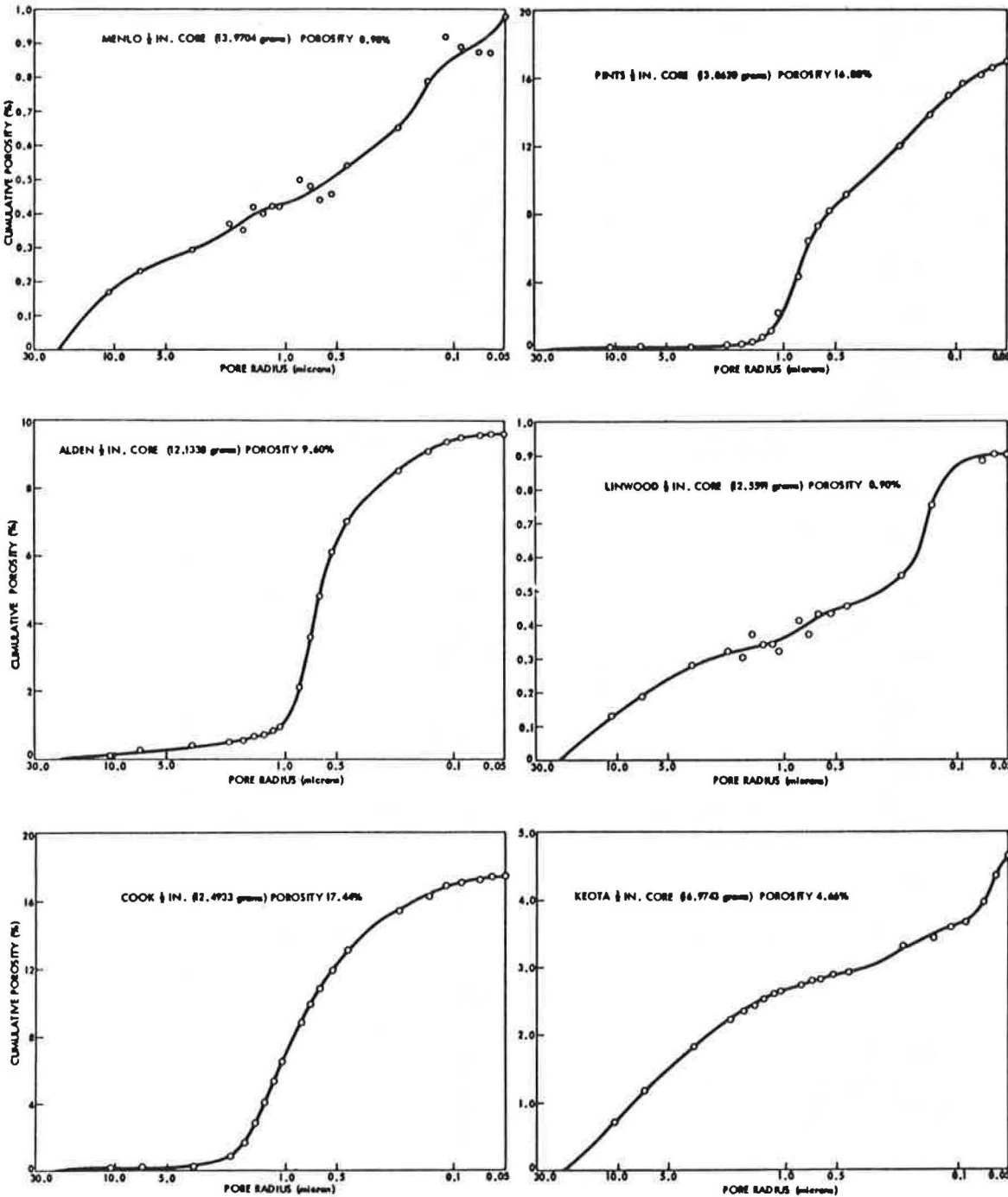
Figure 2. Nonnormalized pore-size distribution.
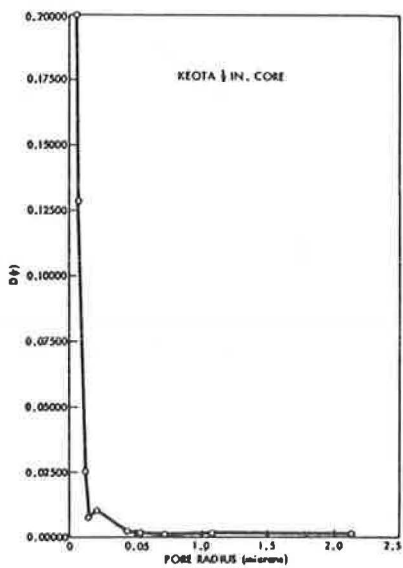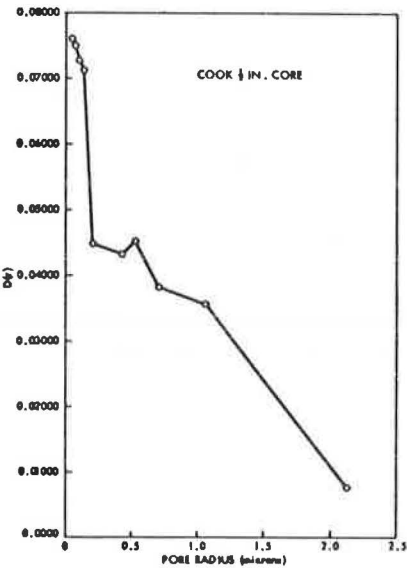
Hysteresis in Mercury Porosimetry—Curves illustrating the phenomenon of hysteresis are shown in Figure 3. If the pores are cylindrical with a uniform diameter or V-shaped, the points of penetration and retraction of mercury in pressure-penetration curve will fall on the same line, provided the advancing and receding contact angles are also equal. However, pores with a narrow throat, the so-called "ink-bottle" pores, would not be expected to empty when the pressure is released and thus are responsible for hysteresis. Estimation of the major dimensions of the interior cavities can be made from the phenomenon of hysteresis. Detailed interpretation of data on individual rock's pore properties, based on the pore-size distribution graphs and hysteresis, can be done and has been reported elsewhere (29).

Asphalt Absorption

As mentioned earlier, asphalt absorption was determined for the $\frac{1}{2}$-in. diameter rock cores by using two methods: (a) bulk-impregnated specific gravity method and (b) immersion method. Two asphalts having penetrations of 85 to 100 (referred to as asphalt A) and 120 to 150 (referred to as aspahlt B) were used to compare their relative absorption by the rock cores. Duplicate determinations of asphalt absorption were done in each test. The results of absorption tests are given in Table 6.

Absorption by Bulk-Impregnated Specific Gravity Method—The percentage of absorption (using asphalt A) varied from a low of 0.30 for Menlo cores to a high of 2.01 for Pints cores. Results of absorption for asphalts of different penetrations (A and B) are shown in Figure 4. The correlation coefficient is 0.9861, which is excellent. There is no appreciable difference in percentage of asphalt absorption as far as the two asphalts are concerned, though the absorption of asphalt B is slightly higher than asphalt A, as expected. This could be because the viscosity difference between the two asphalts at testing temperature (280 F) was too small.

Asphalt Absorption by Immersion Method—The percentage of absorption (using asphalt A) varied from 0.44 for Linwood cores to 2.11 for Pints cores. Results of differential absorptions of asphalts A and B are shown in Figure 4. The correlation coefficient is 0.9505. Again, the slope and intercept of the regression line indicate a general trend of no appreciable difference between absorption of asphalts A and B.

Comparison of Two Methods—Table 6 shows that the absorption values from the immersion method are higher than those obtained by using the bulk-impregnated specific gravity method. Figure 5 shows a comparison of the two methods. The correlation is excellent for asphalts A and B. The correlation coefficients are 0.9883 and 0.9862 respectively. Slopes of the regression lines indicate, in general, a constant difference in the values obtained by two methods. It is indicated that the immersion method gives higher values, which can be taken as the absorptive potentials of the rock cores used in this study. The values obtained by using the specific gravity method can be considered as the "realistic" maximum value (25), which can occur during mixing, hauling, spreading, and cooling of the paving mixture and in service under traffic.

Pore Properties Versus Asphalt Absorption

Porosity in different pore-size ranges has been determined for rock cores as well as the absorption of asphalt by using two methods and two types of asphalt. All these results were put to statistical analysis to find the pore-size ranges or other porosity characteristics that may have some correlation with asphalt absorption. Correlation coefficients and regression coefficients (slope and Y-intercept of the regression line) were determined. It was thought that there could be a pore-size range (or ranges) that is optimum for asphalt absorption.

Correlations

Water Absorption and Asphalt Absorption—Efforts have been made in the past (24, 28) to correlate water absorption of aggregates to asphalt absorption because the former is relatively a very simple standard test. In this study, the linear correlation coefficients range from 0.8398 to 0.9341, which is excellent. However, experience has

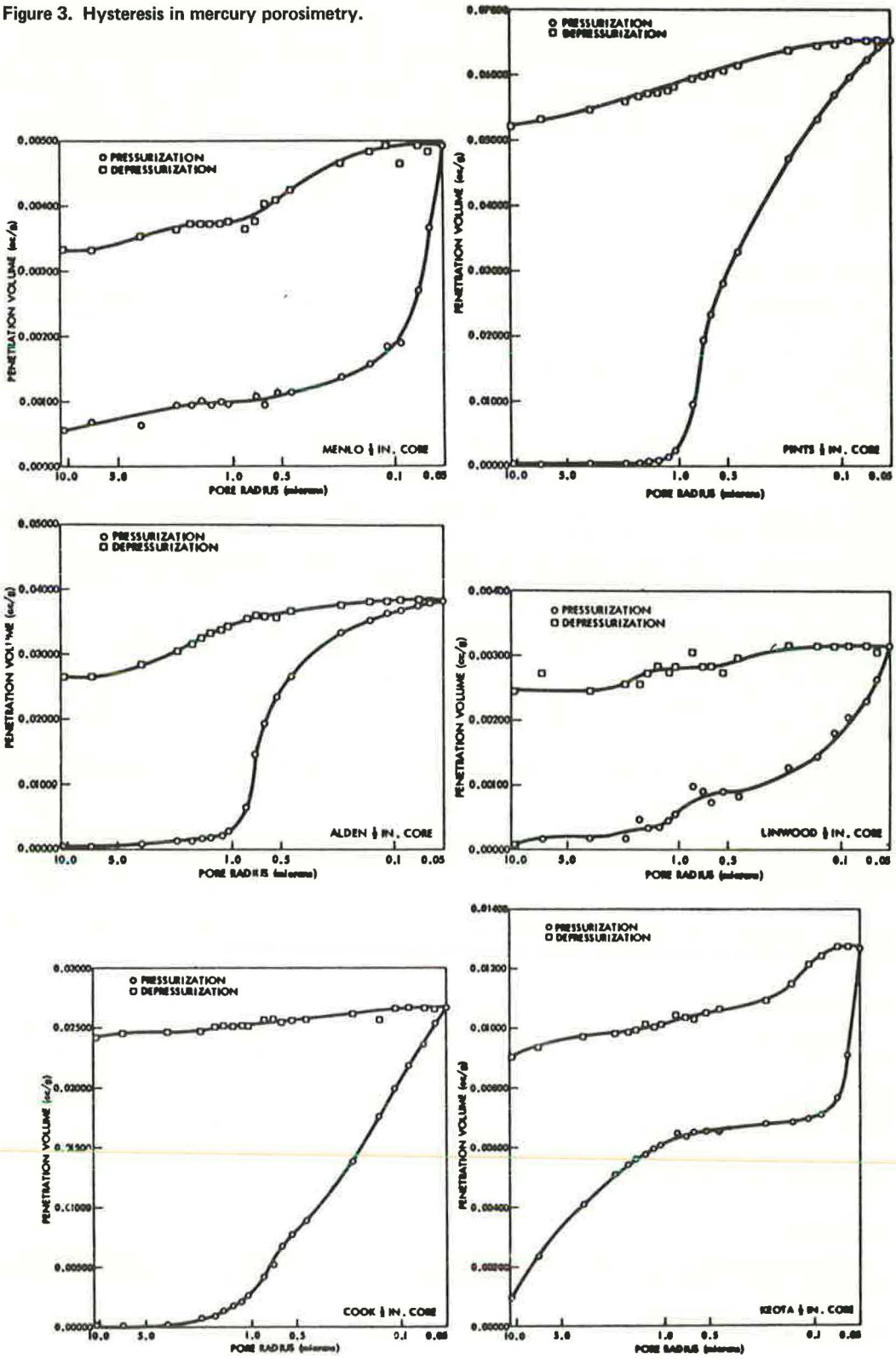Figure 3. Hysteresis in mercury porosimetry.

Table 5. Linear correlation coefficients among main pore properties.

Porosity	Porosity						
	24-Hour Soaked	Mercury-Intrusion	0.7- to 0.05-μm	0.1- to 0.05-μm	1- to 0.05-μm	1- to 0.1-μm	1- to 0.5-μm
24-hour soaked	1.0						
Mercury-intrusion	0.7093	1.0					
0.7- to 0.05-μm	0.7716	0.9553	1.0				
0.1- to 0.05-μm	0.9782	0.5510	0.6510	1.0			
1- to 0.05-μm	0.7405	0.9548	0.9987	0.6128	1.0		
1- to 0.1-μm	0.6733	0.7084	0.9894	0.5341	0.9953	1.0	
1- to 0.5-μm	0.5664	0.9275	0.9566	0.4188	0.9687	0.9854	1.0

Figure 4. Asphalt absorption: asphalt A versus asphalt B.
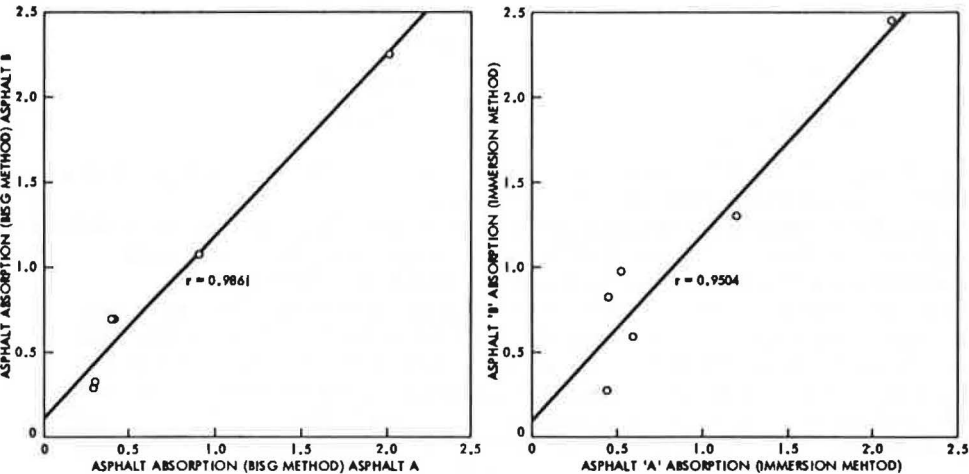

Table 6. Asphalt absorbed by rock cores (percentage by weight of rock cores).

Rock Core	Bulk-Impregnated Specific Gravity Method		Immersion Method	
	Asphalt A	Asphalt B	Asphalt A	Asphalt B
Menlo	0.30	0.30	0.59	0.59
Pints	2.01	2.27	2.11	2.47
Alden	0.91	1.08	1.20	1.31
Linwood	0.30	0.33	0.44	0.28
Cook	0.40	0.70	0.45	0.83
Keota	0.41	0.69	0.52	0.98

Figure 5. Asphalt absorption: bulk-impregnated specific gravity method versus immersion method.
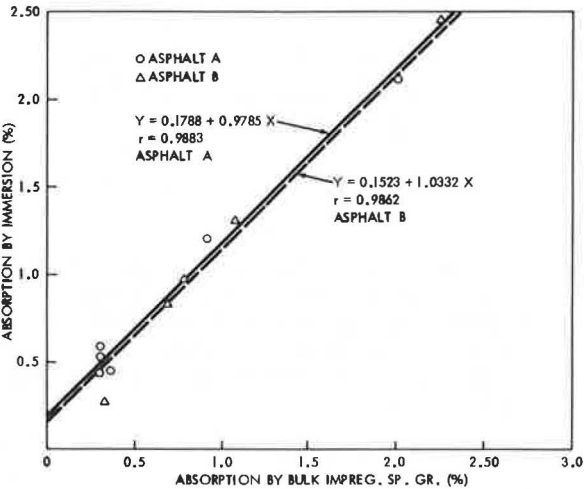
shown that the water absorption is not a reliable test for predicting asphalt absorption because of noted exceptions. Bitumen-water absorption ratios have reportedly ranged from 1 to 100 percent. Aggregates have been reported to show higher bitumen absorption than water absorption in rare cases (28).

Porosity and Asphalt Absorption—Correlation coefficient for porosity in various pore-size ranges and asphalt absorption was determined. It has been noted that the correlation is poor in the following pore-size ranges (in microns): 21 to 11, 21 to 5, 21 to 2, 21 to 1, 11 to 1, and 5 to 1. For the remainder of the pore-size ranges, the correlation coefficients in decreasing order are as follows.

Mercury-Intrusion Porosity Range (μm)	Range of Correlation Coefficients
0.7 to 0.05	0.8760 to 0.7708
1 to 0.05	0.8594 to 0.7595
0.1 to 0.05	0.8566 to 0.7226
1 to 0.1	0.8170 to 0.7247
1 to 0.5	0.7563 to 0.6806
21 to 0.05	0.7136 to 0.5517

The porosity in the 0.7- to 0.05-μm range (as determined by the mercury porosimeter) has excellent correlations with asphalt absorption.

Effective porosity or mercury-intrusion porosity (21- to 0.05-μm range) has correlation coefficients ranging from 0.7136 to 0.5517 with asphalt absorption. However, effective porosity does indicate the general trend of asphalt absorption.

It seems that different pore-size ranges control the absorption of different liquids depending on their viscosities, surface tensions, and contact angles with solids. The correlation coefficients given in Table 5 reveal that 0.1- to 0.05-μm porosity has the best correlation ($r = 0.9782$) with 24-hour soaked porosity and hence may be regarded as the main controlling pore-size range for water absorption as far as limestone rock cores in this study are concerned; porosity in the 0.7- to 0.05-μm range has the best correlation with asphalt absorption ($r = 0.8760$ to 0.7708). As expected, water having good wettability has a lower range of 0.1 to 0.05 μm, whereas asphalt has a controlling range of 0.7 to 0.05 μm.

The equations for regression lines for the linear correlations with a 0.7- to 0.05-μm range are as follows. (X = percentage of porosity in the 0.7- to 0.05-μm range, and Y = percentage of asphalt absorption.)

Pore-Size Range (μm)	Absorption Method	Asphalt	Equation for Regression Line
0.7 to 0.05	Specific gravity	A	$Y = 0.1294 + 0.135 X$
		B	$Y = 0.1977 + 0.1563 X$
	Immersion	A	$Y = 0.3640 + 0.1255 X$
		B	$Y = 0.3362 + 0.1593 X$

In all cases, correlations are better in the case of asphalt B, which has more penetration than asphalt A. Also, absorption values obtained from the specific gravity method have better correlation with the porosity in the preceding pore-size ranges than those obtained from immersion test.

The following conclusions can be drawn from the pore-size and absorption correlations.

1. Pore-size distribution has a direct effect on asphalt absorption. Figure 6 shows the cumulative pore-size distribution of Menlo and Pints cores on the same scale. Considerable difference in asphalt absorption between these two types of rock cores is reflected by the significant variation between the two curves. This is also evident in

Figure 6. Cumulative porosity distribution (Menlo and Pints cores).
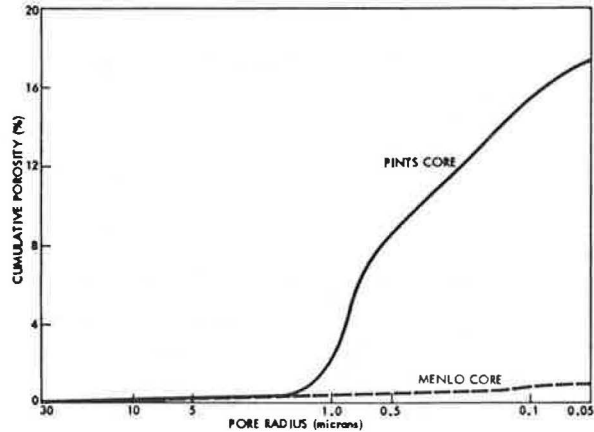

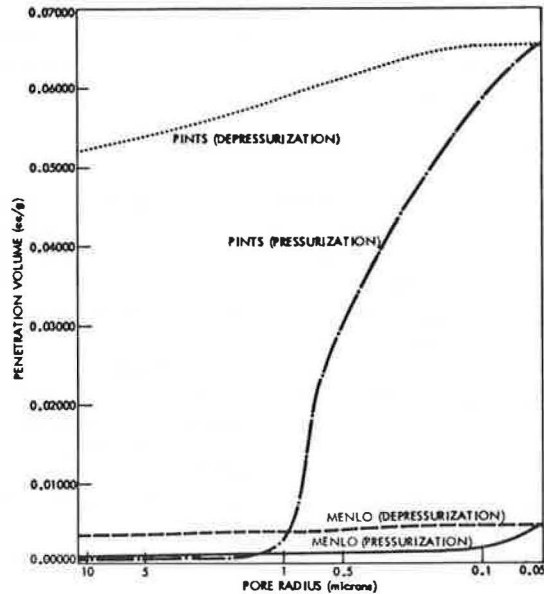Figure 7. Hysteresis in mercury porosimetry (Menlo and Pints cores).

Figure 8. Porosity in 0.7- to 0.05-μm range versus asphalt absorption.
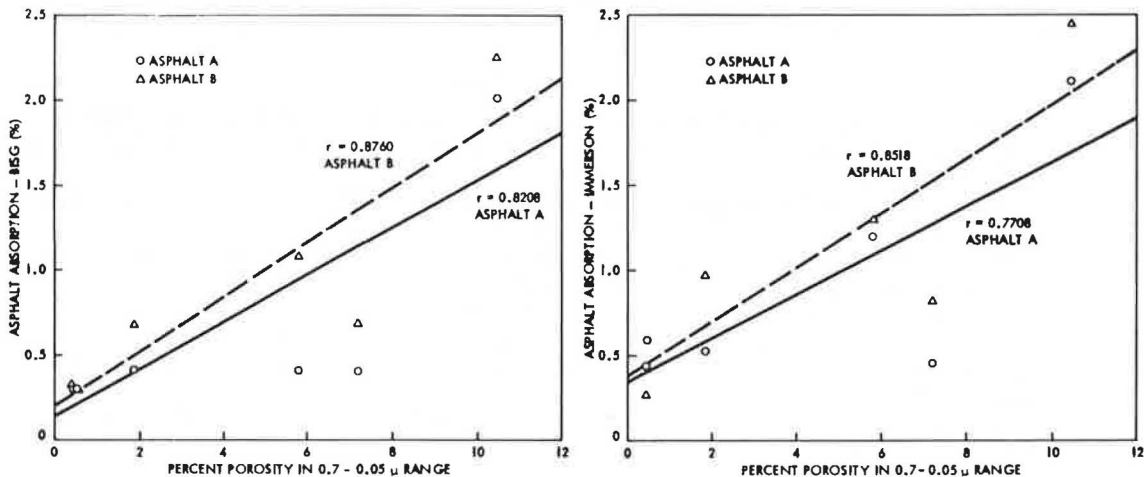
Figure 7, which combines curves of hysteresis in mercury porosimetry of Menlo and Pints cores.

2. Porosity in the 0.7- to 0.05-μm range has a direct effect on asphalt absorption. The relation is linear. Figure 8 shows these relations for both methods.

3. Effective porosity indicates a general trend of absorption of asphalt.

SUMMARY AND CONCLUSIONS

Pore characteristics are the most important properties of aggregates, especially with regard to the absorption phenomenon. Most attempts have been made by the investigators to evaluate aggregate absorption without direct analysis of the pore characteristics. This paper is based on study of absorption of asphalt by aggregates as related to their pore characteristics.

The following conclusions are drawn from the present study.

1. Effective porosity has fair linear correlation with asphalt absorption and thus indicates only the general trend of absorption of asphalt. Cores having more effective porosity are likely to absorb more asphalt and vice versa.

2. Absorption obtained by using the immersion method gives high values that can be regarded as the absorptive potentials of the rock cores, whereas absorption values obtained by using the specific gravity method can be considered as "realistic" maximum values that can occur in certain circumstances that require higher mixing temperatures.

3. Rock cores tend to absorb more asphalt of higher penetration than of lower penetration.

4. Though excellent linear correlations have been found between the percentage of water absorption and asphalt absorption, the former cannot be recommended for predicting asphalt absorption because of the exception found by various investigators.

5. The presence of "ink-bottle" pores is indicated in all cores. The probable dimensions of the pore throats and internal cavities vary from one core to another and seem to affect asphalt absorption.

6. Pore-size distribution of an aggregate has a direct effect on the degree of asphalt absorption. Very good correlation was found between the percentage of porosity in the 0.7- to 0.05-μm pore-size range and the asphalt absorption. This range seems to control the asphalt absorption by limestone aggregates included in this study, whereas pore size in the range of 0.1 to 0.05 μm seems to determine the amount of water absorption. Thus, different pore-size ranges control the absorption of different liquids depending on their viscosities, surface tensions, and contact angles with solids. This emphasizes the importance of pore characteristics in study of absorption by aggregates.

ACKNOWLEDGMENTS

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