Reproduction of Thin Bituminous Surface Course Fabric by Laboratory Compaction Procedures

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The purpose of this study was to determine which laboratory compaction procedure best reproduces the pore size distribution of rolled bituminous sand mix surface courses in the field. Mercury intrusion porosimetry tests were performed on laboratory-compacted samples and field cores to determine their pore size distributions. Comparison of fabric was accomplished by using curve descriptors constructed on differential and cumulative pore size distribution curves. Two gradations, two asphalt types, and four aggregate combinations were evaluated. Laboratory compaction was accomplished by varying the parameters of four laboratory compactors and by compacting at three mix temperatures. Analysis of the results of all compaction methods indicated that the gyratory compactor with a vertical ram pressure of 20 psi and 35 revolutions with a 1-degree gyratory angle plus 5 revolutions of leveling pressure (no applied gyratory angle) best reproduces the fabric produced by the rolling procedures presently used in the field.

Surface sand mixes were used by the Indiana Department of Highways (IDOH) in the late 1950s to economically provide smooth, long-lasting riding surfaces on high-volume roads. These $^5/_8$-in.-thick overlays have 95 percent of the aggregate finer than the No. 4 sieve and, in general, have an asphalt content of 7.5 percent. Pavements with an 8 to 12 percent air voids content display good friction numbers without compromising the stability of the pavement (*1*, *2*). After having performed satisfactorily for many years, sand mix overlays have begun to display problems in service, especially on a section of Interstate highway. These problems consist of blistering and delamination distress under high-speed truck traffic. Investigations indicated a difference of densities between the top and the bottom portions of the surface course and a horizontal plane of failure at middepth of the overlay. These problems prompted a study of the effects of compaction procedures and mix designs on the performance of these sand mix overlays.

It was believed that the distribution of pore sizes within the compacted surface course could be used to characterize the "fabric" of that material and that the fabric could be related to performance. This is a carry-over from geotechnical engineering, which has further found that compaction equipment and procedures uniquely determine the distribution of pore sizes. Mercury intrusion porosimetry is commonly used to determine the pore size distribution of porous materials, and it can also be used for compacted bituminous paving mixtures. The pore sizes of a bituminous mixture are generally larger than several tens of microns, sizes commonly termed macropores, and are rapidly and economically intruded by low-pressure porosimetry techniques. The asphalt pavement industry has long debated which laboratory compaction procedure best replicates the fabric developed by field compaction procedures. The answer to this question is the major objective of this study. Other investigators have been able to show good correlation between porosimetry results and behavior characteristics (*3*–*5*). Thus reproduction of the fabric in the laboratory and correlation of fabric to in-service performance of the material could provide good feedback for the mix design process.

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THEORETICAL BASIS OF MERCURY INTRUSION POROSIMETRY

The theory of Mercury intrusion porosimetry has been attributed to Washburn (*6*, pp. 52–60), who pointed out that mercury would not voluntarily intrude pores of particulate materials. The high surface tension of nonwetting liquids, such as mercury, requires such liquids to be forced into the pores. Using a cylinder as a geometric model of a pore, a simple equation was developed relating the size of pore being intruded to the applied pressure. The resulting Washburn equation yields the diameter of an equivalent cylindrical pore that would be intruded at that pressure (in real materials pores are not cylindrical):

$$P = \frac{-2\gamma \cos(\theta)}{r} \tag{1}$$

where

P = pressure causing the intrusion (psi),
r = radius of equivalent cylindrical pore (in.),
γ = surface tension of mercury (lb/in.), and
θ = contact angle between mercury and pore wall (degrees).

MATERIALS

Asphalt Binders

A 7.5 percent asphalt content is the midpoint of the range allowed by the Indiana State Highway Commission (IDOH) Standard Specifications (*7*) and was used throughout this study. Two asphaltic binders are used in sand mix overlays in Indiana:

AC-20 and AE-60. The AC-20 was obtained from the Amoco Oil Company. The AE-60 (IDOH designation) is a high-float, medium-setting asphalt emulsion formulated and provided by the laboratory of McConnaughay Emulsions in Lafayette, Indiana. The basic properties of these binders follow: Kinematic viscosity of the AC-20 is 236.0 cSt at 135°C (275°F); its penetration is 60 at 25°C (77°F), 100 g, and 5 sec-min. The AE-60 has 70.7 percent residue by distillation; penetration of residue is 60 after distillation at 25°C (77°F), 100 g, and 5 sec-min.

Aggregates

Two materials were used as aggregates for the bituminous mixture in this study: local material and crushed agricultural limestone (agg lime). The local pit-run gravel-sand was obtained from the Western Material Company in West Lafayette, Indiana. This material is a terrace gravel-sand deposited by the early Wabash River and consists of approximately equal amounts of calcareous and siliceous minerals. The crushed agg lime was quarried in Indiana and is used in proportions of up to 20 percent of the total aggregate in the mix for the purpose of obtaining required Florida bearing values (*8*). This study combined the two aggregates in proportions of 100 percent local material and 90 percent local, 10 percent agg lime to obtain the required comparisons with field cores. The properties of the aggregate blends are given in Table 1.

TABLE 1 PROPERTIES OF MINERAL AGGREGATE

Property	Local Gravel-Sand	90% Local and 10% Agg Lime
Apparent specific gravity	2.661	2.758
Bulk specific gravity (SSD)[a]	2.615	2.632
Absorption (%)	1.08	0.96
Florida bearing values		
G2	64.0	66.0
FM	67.0	69.0

[a]Saturated surface dry.

Job Mix Formula

Two gradations, representing those commonly used by the IDOH on sand mix projects, were examined. The first gradation, G2, was based on pavement sections showing good performance characteristics. The second gradation, FM, was based on a fineness modulus concept that has only recently been introduced. The FM and G2 gradation curves, as well as the Indiana State Highway Commission (IDOH) standard specifications, are shown in Figure 1.

COMPACTION PROCEDURES

Field Compaction

The procedures commonly specified by IDOH for compaction of HAE Type IV and HAC Type D surface sand mixes require two passes of a three-wheeled steel-wheeled roller followed by two passes of a tandem roller (*9*). The three-wheeled steel-wheeled rollers must have dry roller weights (the two rear rollers) of 300 lb per inch width of roller, and the tandem roller is required to have a weight of 10 tons (*7, 10*).

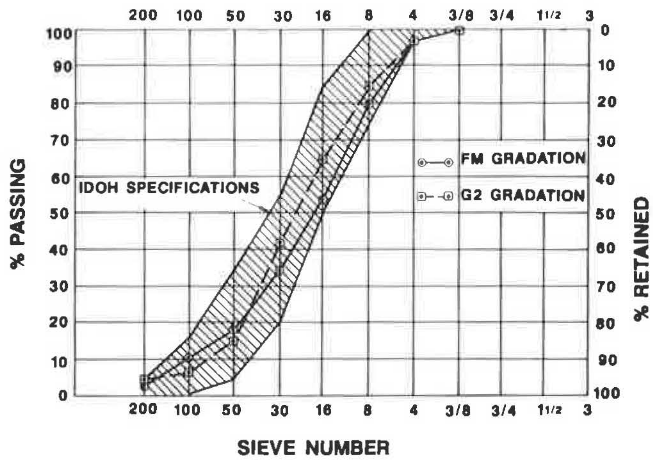

FIGURE 1 Gradation curves and specifications.

Laboratory Compaction

Laboratory specimens were compacted in gyratory, California kneading, vibratory, and Marshall (impact) compactors. Each of these uses significantly different procedures for imparting energy to densify the mix, and this offers the possibility of producing different fabrics. The compaction parameters used in this study to create samples with a density of 135 pcf, the target density for controlling compactive effort, follow:

- Gyratory compactor (at 1-degree gyratory angle)
  20-psi vertical pressure, 35 revolutions
  50-psi vertical pressure, 20 revolutions
  70-psi vertical pressure, 15 revolutions
- Kneading compactor (with 5,000-lb leveling load)
  60-psi contact pressure, 150 tamps
  80-psi contact pressure, 120 tamps
  90-psi contact pressure, 90 tamps
- Marshall compactor
  30 blows per side, 10-lb hammer, 18-in. free-fall
  25 blows per side, 10-lb hammer, 18-in. free-fall
- Vibratory compactor (50-psi air pressure)
  1/4 in./min advance rate, 15,000-lb max load
  1/2 in./min advance rate, 15,000-lb max load

The parameters for all compactors are well below typical mix design compaction parameters. In addition to variations in the independent compactor variables, the lift thickness can influence the efficiency with which a compactor arranges and compacts particles. Thus the amount of material compacted to form a sample was varied between 500 and 1050 g. Three compaction temperatures, 230°F, 180°F, and 150°F, were investigated as well.

The major operational aspects of the gyratory testing machine (GTM) have been thoroughly discussed in the literature (*11, 12*) and in ASTM D 3387-74T. The GTM has three variable parameters: vertical ram pressure, number of revolutions, and gyratory inclination angle. As a guide, a minimum of 20 revolutions is required to account for initial roller compaction (*13*). To achieve the target density only, low compaction energies were required. The gyratory angle was held constant at 1 degree as suggested (*10*) because the gyratory action was

ineffective with less applied angle. An additional five revolutions of leveling pressure (no applied gyratory angle) were applied at the end of each compaction procedure.

Operation of the kneading compactor was modified for this study, but it basically followed the procedure of ASTM D 1561. The variable parameters for this procedure are maximum contact pressure, number of tamps, and leveling load. The tolerable maximum contact pressure was 90 psi, well below the 500-psi standard pressure required by the Hveem method. Higher pressures resulted in the tamping foot punching through the mixture and pulling it out of the mold on the upstroke. A maximum leveling load of 5,000 lb, applied after the mix was kneaded, was necessary to produce samples that met the density criterion. The number of pressure applications required to sufficiently work the mixture was previously determined to be 150 (*14*). Because of physical limitations of the kneading compactor, 60 psi was the minimum contact pressure capable of compacting the material.

Samples were compacted in the Marshall compactor as prescribed in ASTM D 1559. This compaction procedure has become a major component of procedures for bituminous mix design. The variable parameters are weight of hammer, free-fall distance, and number of impacts per sample side. The limited number of hammers and the fact that the automatic Marshall compactor used in this study could only accommodate a free-fall distance of 18 in. limited the number of combinations of parameters investigated.

The vibratory compactor was designed to simulate the action of vibratory rollers. The variable parameters for this procedure are maximum applied load, rate of vibrating unit advancement, and air pressure causing vibration. The vibratory action was obtained by compressed air causing a piston to vibrate vertically resulting in the acceleration of the compactor head. Vibration during compaction was possible because of the insertion of a neoprene cushion on top of the vibrating piston unit. The vibratory action was most effective at low vertical pressures. As the vertical load was increased to its limiting value of 15,000 lb (due to the compressibility of the neoprene cushion) the vibrating action decreased. Compaction of the samples is achieved by the advance of the vibrating unit through the use of the Riehle Machine static compactor.

MERCURY INTRUSION POROSIMETRY

The porosimeter system consists of high-vacuum pump, vacuum-to-atmospheric manometer, McCleod gauge, immersing device, and vacuum stopcock that opens to the atmosphere, all of which are connected by vacuum tubing (Figure 2). The manometer shows the absolute pressure in the system to the nearest millimeter of mercury. The McCleod gauge is used for readings of high vacuum pressure, to the nearest 0.01 mm Hg, in the system. The immersing device houses the penetrometer and a quantity of mercury sufficient to surround and fill the penetrometer when the immersing device is tilted into its filling position. One vacuum stopcock allows the entry of pressure into the system by opening to the atmosphere. The atmospheric pressure enters slowly because of the small orifice through which it must pass, allowing the desired pressure increments to be easily attained. The penetrometer is an accurately calibrated glass stem with a sample-holding chamber. The entire system must be tightly sealed.

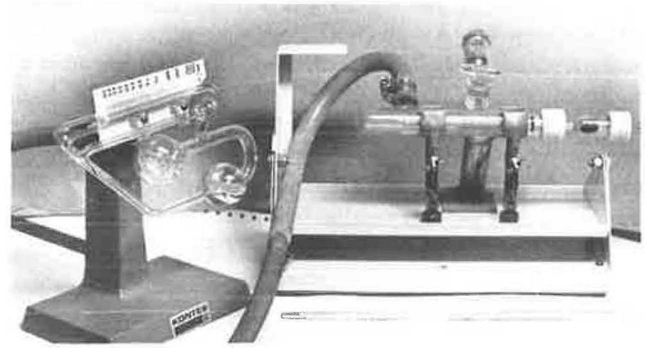

FIGURE 2 Porosimeter apparatus.

Sample Preparation and Testing

Porosimetry specimens about 1 cm × 1 cm × 1 cm in size were obtained from compacted material, either field cores or laboratory samples. This was accomplished by freezing the compacted material to −10°F to produce a brittle condition that made it possible to crack the material without disturbing the particle arrangement. Specimens from laboratory-compacted samples were then desiccated for not less than 24 hr to remove most of the volatile gases. The field samples were thought to be sufficiently cured already because 1 month or more had elapsed from the time of construction to the time the cores were tested.

After the weight measurements were obtained, a specimen was placed in the apparatus, the system was sealed from the atmosphere, and the vacuum pump was turned on to evacuate the air within the system. A vacuum pressure of at least 0.02 mm Hg was obtained within the system before 20 mm of atmospheric pressure was applied to force mercury into the penetrometer to surround the test specimen. Light tapping of the penetrometer end was required until the reading on the penetrometer stem stabilized to assure the mercury intruded all voids at this and each additional increment of pressure applied to the system.

The pressure increments applied to a test specimen must reflect the predominant pore diameters within the sample. The spacing must be small enough to obtain sufficient curve descriptor accuracy, yet large enough to allow the differential volumes intruded to be significant and the variability to be kept reasonable. The quantity controlling this even spacing on the logarithmic x-axis is c in Equation 2. Equally spaced data points along this axis allow simple geometric constructions for fabric descriptors to be comparable anywhere on these plots. A value for c of 0.099 was selected because previous investigations indicated that this would produce meaningful, yet sensitive, descriptors.

$$\frac{P_i}{P_{(i-1)}} = 10^c \qquad (2)$$

where

P_i = ith increment of pressure,

$P_{(i-1)}$ = previous pressure increment, and
c = constant of increment.

Comparison of Pore Size Distribution Data

The differential and cumulative pore size distribution (PSD) curves (Figures 3 and 4) were generated by a computer program in which each of the data points from a porosimetry test constituted one data point. Descriptors, characterizing the distribution curves, were created by simple geometric constructions; these were used to compare curves from various test conditions. Work performed previously (*15*) determined that the greatest effort should be directed toward the differential curve because this plot appears to be the most sensitive to differences in fabric. The descriptors used for this study were selected to measure the quantities believed to be influential in the performance of sand mixes and permit the differentiation of material fabrics. These descriptors are defined next.

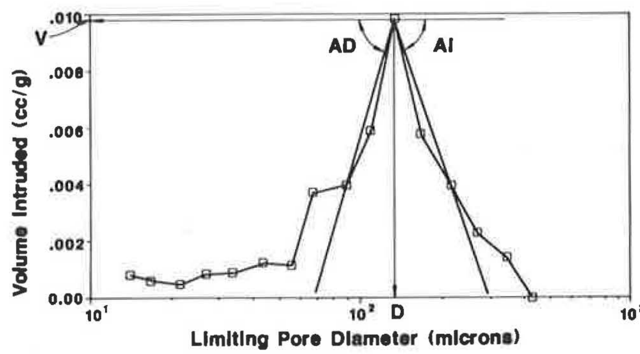

FIGURE 3 Differential PSD curve and descriptors.

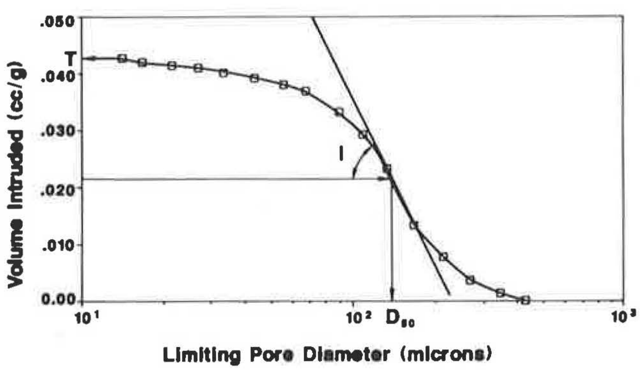

FIGURE 4 Cumulative PSD curve and descriptors.

LD is the logarithm of the pore diameter, shown as D in Figure 3, at which the peak frequency occurs. The conversion of D to its logarithm occurs after the value of D has been interpolated from the x-axis. This descriptor is probably related to the permeability of the mixture.

V/T is the ratio of the volume intruded at the peak frequency to the total volume intruded in the sample. The two descriptors, V and T, in Figures 3 and 4, respectively, are combined to form this descriptor. This measurement and the descriptors AI and AD determine the concentration of pores about the maximum frequency diameter.

AI is the onset angle and AD is the offset angle to the peak; both are measured on the differential plot. These descriptors are obtained by constructing a line through the peak frequency and two data points on either side of this peak frequency.

LD_{50} is the logarithm of the pore diameter, shown as D_{50} in Figure 4, where 50 percent of the intruded volume lies in pores of larger sizes. Again, D_{50} is interpolated from the x-axis and is converted to its logarithmic value for comparison purposes. This quantity is found by multiplying T by 0.5 to obtain H. The diameter corresponding to the intersection of H and the cumulative porosity curve was defined as D_{50}.

T/P, the percentage of total voids intruded, is not shown on these plots. This percentage of interconnected voids is believed to be a critical parameter in sand mixes for reasons of permeability and possible performance. This descriptor uses P, the total volume of voids in the sample, a value computed separately, and T, shown in Figure 4.

ANALYSIS OF RESULTS

The results presented represent work performed with the following combinations of materials: G2, AE-60 with both local and 90-10 aggregate blends as well as FM, AC-20, and local material. The means and standard deviations for each set of porosimetry samples, laboratory and field, having similar gradation and aggregate combinations are given in Tables 2–4. The number of porosimetry tests performed on the various compacted samples was 12 tests on field samples and from 5 to 7 tests on laboratory samples. Within each table of results, the means of the various laboratory descriptors were checked against that of the field descriptors using a 95 percent confidence interval to determine the equivalence, or otherwise, of the laboratory and field mean values. The underscored numbers indicate the descriptor means that are statistically equivalent to that of the field cores. The comparisons that were made between laboratory and field samples for FM gradation (Table 4) have only limited applicability because of the higher densities of the specimens compacted in the laboratory. This higher density was obtained even though the compaction parameters were reduced to extremely low values.

The results for samples with a 90-10 combination of aggregate and AE-60 as a binder indicate that as the applied pressure is reduced and the time of compaction increased, the fabric obtained approaches that of the field cores. This is true for both the gyratory and kneading compactors with the first being more sensitive. The trend is not followed, however, for the compacted samples containing only local material and is, indeed, reversed.

Gradation changes produced noticeably different pore size distribution curves in both the field and the laboratory samples. The FM gradation specimens had less pore volume concentrated about the peak frequency diameter. The differences in curves produced by the two gradations are much more pronounced in the laboratory samples.

Compaction temperatures had no influence of the fabric created in the laboratory. Lower compaction temperatures have a slight tendency to increase the percentage of voids intruded in a test specimen. This could be the result of nonuniform distribution of binder within a compacted sample. Also, the amount of material compacted to form a sample had little influence on the resulting pore size distribution.

TABLE 2 90-10 G2 BLEND RESULTS

	LD	V/T	AI	AD	LD_{50}	T/P
Field cores	2.122	0.215	65.5	65.2	2.164	0.752
	(0.106)	(0.022)	(6.72)	(9.16)	(0.069)	(0.084)
Gyratory at 230°F						
20 psi for 35 revs	1.984	0.221	37.8	44.5	2.082	0.427
	(0.126)	(0.026)	(14.72)	(21.16)	(0.046)	(0.066)
30 psi for 20 revs	2.130	0.244	53.2	65.2	2.129	0.457
	(0.065)	(0.022)	(11.65)	(6.89)	(0.118)	(0.122)
500-g sample, 30 psi	1.919	0.165	53.7	56.9	2.016	0.674
	(0.106)	(0.019)	(14.60)	(10.50)	(0.084)	(0.088)
Kneading at 230°F, 90 psi for 3 min	1.913	0.224	46.3	39.6	1.979	0.395
	(0.136)	(0.047)	(7.61)	(16.90)	(0.076)	(0.086)
Kneading at 180°F, 90 psi for 3 min	2.047	0.216	42.4	43.3	2.112	0.459
	(0.107)	(0.019)	(19.19)	(18.70)	(0.057)	(0.115)
Vibratory at 230°F, 15,000 lb 0.25 in./min	2.102	0.143	38.6	23.8	2.055	0.671
	(0.096)	(0.021)	(24.30)	(13.40)	(0.040)	(0.153)
Marshall at 230°F, 25 blows/side	2.040	0.228	49.2	52.1	2.108	0.553
	(0.056)	(0.043)	(9.40)	(16.20)	(0.038)	(0.051)

NOTE: Standard deviations are in parentheses. Underscored values are equivalent to the field mean within a 95 percent confidence interval.

TABLE 3 LOCAL G2 BLEND RESULTS

	LD	V/T	AI	AD	LD_{50}	T/P
Field cores	2.069	0.222	57.3	55.9	2.110	0.674
	(0.069)	(0.030)	(11.86)	(15.80)	(0.051)	(0.149)
Gyratory at 230°F						
20 psi for 35 revs	2.034	0.200	44.0	51.4	2.070	0.486
	(0.110)	(0.024)	(10.59)	(9.23)	(0.072)	(0.040)
30 psi for 20 revs	2.019	0.196	39.8	41.9	2.050	0.484
	(0.115)	(0.022)	(21.19)	(18.51)	(0.052)	(0.075)
70 psi for 15 revs	1.969	0.197	32.8	26.1	2.030	0.430
	(0.110)	(0.026)	(12.10)	(11.35)	(0.061)	(0.080)
Gyratory at 180°F, 20 psi for 35 revs	1.927	0.174	46.2	41.9	1.907	0.530
	(0.155)	(0.028)	(15.02)	(19.47)	(0.096)	(0.029)
Kneading at 230°F						
90 psi for 3 min	1.870	0.150	44.6	44.7	1.908	0.563
	(0.095)	(0.014)	(11.14)	(11.70)	(0.087)	(0.046)
60 psi for 5 min	1.883	0.152	45.7	32.6	1.889	0.572
	(0.092)	(0.014)	(11.90)	(13.15)	(0.064)	(0.031)

NOTE: Standard deviations are in parentheses. Underscored values are equivalent to the field mean within a 95 percent confidence interval.

TABLE 4 LOCAL FM BLEND RESULTS

	LD	V/T	AI	AD	LD_{50}	T/P
Field cores	1.934	0.227	52.3	62.3	2.010	0.568
	(0.090)	(0.036)	(14.59)	(9.35)	(0.044)	(0.058)
Gyratory at 230°F, 20 psi for 35 revs	1.706	0.124	19.8	17.9	1.785	0.306
	(0.138)	(0.028)	(14.24)	(13.36)	(0.042)	(0.045)

NOTE: Standard deviations are in parentheses.

A consistent and important observation made from the results is that when the pores were concentrated about the peak, a higher percentage of the voids was intruded (interconnected). This trend is consistent for compaction temperatures, compactors, and pressure-time relationships.

Tests previously conducted on cores from pavement surfaces that performed well and poorly indicate that the pavements that performed poorly had larger volumes of pores at the peak. The set of samples obtained from areas that performed well had pores more evenly distributed among the various pore diameters. On the basis of these limited results, it is believed that the FM gradation could prove to be stable when subjected to service loads.

SUMMARY AND CONCLUSIONS

Two conclusions can be drawn from the results obtained in this study. First, the gyratory compactor with a 20-psi vertical ram pressure for 35 revolutions at a 1-degree angle of inclination plus 5 leveling revolutions (no gyratory angle) best duplicates the fabric obtained by the field compaction procedures currently in use with Gradation G2 mixes. The kneading compactor also produces some fabric characteristics that are not too different from field fabric. Although the fineness modulus gradation fabric was not matched as well by the GTM procedure, these investigators believe that the GTM, used at low vertical ram pressures, offers the best opportunity to reproduce sand mix fabric for a range of gradations.

Second, a high concentration of pores near the peak frequency diameter, a characteristic common in the fabric created by field rolling of G2 surface courses, allows the possibility of redistribution of these pores on compaction by traffic. These pores are not always redistributed, which results in mixed performance of these pavements. When compaction due to the action of traffic changed the fabric to a less pronounced peak on the pore size distribution curve, acceptable performance was observed. When no redistribution of the pore sizes occurred in the fabric, poor pavement performance was observed. Tests performed on newly paved overlay sections that consisted of aggregate meeting the FM gradation specifications revealed less pore volume located near the peak frequency diameter. This lower initial volume near the peak should be associated with less variability and better in-service performance characteristics. The authors believed that the compaction of thin overlays and the gradation used should allow a low concentration about the peak frequency diameter to obtain pavements that perform well. One note of caution: only a very few test results were available on the characteristics of pavements that performed well and poorly in the field.

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