Characterization of Hot-Mixed Open-Graded Asphalt Mixtures

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A detailed laboratory investigation was undertaken to study the effects of different mix components on several engineering properties of open-graded asphalt mixtures. Among these properties are density, air voids, Marshall stability and flow, resilient modulus, tensile strength, and permeability. Properties of the open-graded mixture were compared with those of dense-graded mixtures and open-graded cores obtained from a porous pavement experimental test section. The asphalt content and aggregate gradation influenced the density, air voids, Marshall stability, instantaneous and total resilient moduli, and coefficient of permeability of laboratory-prepared open-graded specimens. The tensile strength was not affected by either the asphalt content or the aggregate gradation at a significance level of 0.05. The resilient characteristics were found to be highly affected by temperature. Lower densities and consequently higher air voids were measured on the open-graded cores than on laboratory-prepared specimens containing similar material components. Lower Marshall stability and resilient moduli were measured on the cores. Theoretical analysis revealed significant differences between the predicted performance of open-graded and dense-graded asphalt pavements. Thicker layers were required for the open-graded asphalt mixture to produce the same vertical deformation on top of the subgrade. The study resulted in understanding basic engineering properties of open-graded asphalt mixtures so their use in pavement structural layers would be based on a more rational procedure.

Among the many effects of urbanization on the environment is the increased runoff caused by the lower infiltration of paved surfaces such as streets, parking lots, and building roofs (*1*). As a result, existing sewer systems are overloaded, and new systems are expensive to construct. These problems are especially obvious in arid areas where typical storms are of high intensity and short duration in the summer, which results in high peak discharge, and of long duration and low intensity in the winter, which creates a large volume of runoff (*2*). Both cases require large highway drainage structures that typically account for more than 35 percent of the total cost of construction of highway projects in urban areas.

Porous pavements consisting of open-graded surface, base, and subbase layers have been suggested as a less costly alternative to conventional pavements (*1*). The concept behind this alternative is to eliminate highway runoff or to design the runoff to be the same as that of the original site. In addition to adequately carrying traffic loads, the main purpose of the porous pavement is to absorb, store, and dissipate storm waters into the ground. Water supplied to the pavement surface drains vertically through interconnected voids and is stored in the base and subbase until it can percolate into the subgrade (*3*). The permeability of the porous pavement, which is typically controlled by that of the surface layer, is designed so that water passes through at a rate faster than the rate of water supply to the pavement surface in order to prevent water ponding. Other advantages of porous pavements include higher skid resistance, better visibility of pavement marking during rain, and lower hydroplaning potentials in comparison with conventional asphalt concrete pavements (*4*).

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BACKGROUND, PROBLEM STATEMENT, AND OBJECTIVES

Previous porous pavement applications have been generally limited to parking lots and driveways (*1, 3*). Some problems were reported, such as scuffing of the pavement surface due to steering and braking actions of traffic and reduction in permeability with time due to clogging of the pavement pores.

In an effort to study the feasibility of the porous pavement for controlling runoff on major roads, the Arizona Department of Transportation (ADOT) established a 3,500-ft-long three-lane-wide experimental test section on the northbound lanes of Arizona Avenue in Chandler, Arizona. The average daily traffic (ADT) is 25,000 to 30,000 vehicles with 7 to 8 percent trucks. The pavement consisted of a thick open-graded surface course supported by an open-graded asphalt-stabilized base on top of an open-graded aggregate subbase (Figure 1). The surface layer

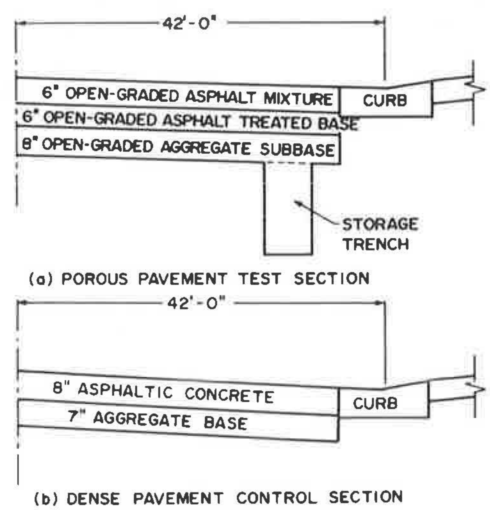

FIGURE 1 Typical cross section of ADOT's experimental porous pavement.

consisted of 6 in. of hot-mixed, open-graded asphalt mixture with a maximum aggregate size of 3/8 in. The open-graded mix was compacted using static rollers to avoid breaking of aggregate particles. The subgrade consisted of clayey material with low permeability, and it was not saturated during construction. The pavement was designed to control the runoff expected from a 100-year storm or two 10-year storms on consecutive days. The conventional asphalt concrete pavement located on both ends of the porous pavement test section was designated as the control section. It should be noted that the ADOT experimental pavement is quite different from most previous porous pavements, which consist of a porous aggregate base and a thin porous asphalt surface. Also, the open-graded asphalt mixture has been previously used in thin friction courses to increase skid resistance and to improve riding quality (*5, 6*).

Shortly after the construction of the two outside lanes of pavement in May 1986 and after a few weeks of stage construction detour traffic, rutting problems occurred that led to the temporary closure of the roadway as a stage construction detour. Rut depth ranged between 3/8 and 1 in. as shown in Figure 2. To eliminate these depressions and to satisfy design thickness requirements, the open-graded surface layer was further compacted using vibratory rollers and then overlaid with a 1-in.-thick layer of the same open-graded mixture and compacted with a vibrating roller.

FIGURE 2 Example of rutting resulting from stage construction detour traffic before final 1-in. lift of surface.

Rutting was not the only problem encountered. Difficulties were observed during the placement and compaction of the surface layer. The mixture appeared to be rich in asphalt and failed to harden.

MIX DESIGN OF HOT-MIXED, OPEN-GRADED ASPHALT MIXTURES

The mix design method employed by many highway agencies has produced satisfactory results for thin friction courses. However, the response of these thin layers to load is different than that of thick layers. Most of the load applied to thin layers, with approximately the same thickness as the maximum aggregate size, is carried by large aggregate particles that transmit the load to the next layer of the pavement structure. On the other hand, the stability of thick layers is governed by other factors, especially the interlocking effect of aggregate particles. Therefore open-graded asphalt mixtures that are intended for use in thick layers require different mix design procedures than do open-graded mixtures placed in thin layers.

For friction courses, the optimum asphalt content of open-graded asphalt mixtures is usually computed from empirical formulas developed from field experience. These formulas are mainly a function of the surface capacity (K_c) of the coarse aggregate fraction of the mixture. In addition to a design formula developed by FHWA (*7*), several states have developed their own formulas based on their past experience. The formula used by ADOT to determine the asphalt content for friction courses was also used for the open-graded mixture of the porous pavement experimental project. This formula is (*8*)

$$AC = (1.5\ K_c + 3.5) \times 2.65/G_{oc}$$

where

AC = asphalt content by weight of total mix,
K_c = surface capacity of the coarse aggregate fraction, and
G_{oc} = combined aggregate oven-dried specific gravity.

Little information is available in the literature on the structural ability of the hot-mixed, open-graded asphalt mixture. Most of the available literature on the strength of open-graded mixtures is concerned with emulsion mixtures (*9*) and asphalt-stabilized aggregate bases (*10*). A better understanding of the mechanical properties of open-graded asphalt mixtures and the factors affecting these properties is still needed.

The objectives of this study are to

1. Evaluate the mechanical characteristics of cores obtained from the surface layer of the experimental porous pavement constructed by ADOT;
2. Compare the properties of field and laboratory specimens prepared with the same materials and proportions in order to detect construction deficiencies;
3. Examine the effect of asphalt content and aggregate gradation on the permeability, strength, and stability characteristics of the hot-mixed, open-graded asphalt mixture; and
4. Compare the strength parameters and the thickness requirements of the hot-mixed, open-graded mixture with those of the dense-graded mixture in order to evaluate the feasibility of placing the open-graded mixture in thick layers.

LABORATORY CHARACTERIZATION

The main part of this investigation was a laboratory evaluation of certain engineering properties of the hot-mixed, open-graded asphalt mixture. The study also involved the use of the mixture properties to examine the structural ability of the open-graded asphalt mixture compared with that of the dense-graded asphalt concrete.

Response Variables

The response variables or the measured mixture properties were selected in order to achieve a better understanding of the stability, strength, and permeability characteristics of the hot-mixed, open-graded asphalt mixture. These properties include

1. Density,
2. Air voids,
3. Marshall stability and flow,
4. Resilient modulus at 41°F and 77°F,
5. Tensile strength at 77°F, and
6. Coefficient of permeability.

Independent Variables

Two independent variables or factors were selected for the evaluation of the open-graded asphalt mixture, asphalt content and aggregate gradation. A third factor, test temperature, was also considered during the resilient modulus evaluation.

Because field observations indicated that the mixture was too rich in asphalt, four levels of asphalt content, based on the weight of oven-dried aggregates, were considered in this study: 4.0, 4.5, 5.0, and 5.7 percent. The latter asphalt content is the one used in the field. Two aggregate gradations were also used.

Initially, the resilient modulus evaluation was intended to be performed at three temperatures: 41°F, 77°F, and 104°F according to the ASTM D 4123 method. However, the open-graded mixture was unstable at temperatures higher than 90°F. For this reason, the evaluation was performed only at the lower two temperatures.

The dense mixture examined in the course of this investigation was similar in both aggregate grading and asphalt content requirements to the dense mixture used in the control section of ADOT's porous pavement project. The laboratory evaluation was performed only at the Marshall optimum asphalt content, which is equal to 5.7 percent by weight of aggregate. Note that the optimum asphalt content was the same for both open-graded and dense-graded mixes, although they were designed using two different methods. Because the surface area of the open-graded aggregate is less than that of the dense-graded aggregate, the amount of asphalt needed to coat the aggregate particles should be smaller for the open-graded mix. However, the open-graded design formula incorporates additional asphalt to counter the fast deterioration of open-graded mixes.

Aggregates

Representative aggregate samples were obtained from approved stockpiles for ADOT's porous pavement project. Strict specifications applied to the quality of the aggregates in the field as well as in the laboratory. At least 90 percent of the aggregates retained on the No. 8 sieve was required to have one or more fractured face, which was produced by crushing, in an effort to reduce mixture stability problems. Two open and one dense aggregate gradations were used in the laboratory (Figure 3). The first open gradation, with a maximum size of 3/8 in. (Gradation A), was identical to the gradation used in the field. This gradation was determined from quality control field records such as those on binder extraction tests performed on production samples. The second open gradation with a 3/4-in. maximum size (Gradation B) was selected from the middle of the open-gradation specification band of ADOT. The third gradation was dense (Gradation C) with a 3/4-in. nominal maximum aggregate size, and was similar to the gradation used on the control section of the porous pavement project. Table 1 gives a summary of the apparent (G_{APP}), saturated surface dry (G_{SSD}), and oven dry (G_{OD}) bulk specific gravities, as well as water absorption (P) for Gradations A, B, and C.

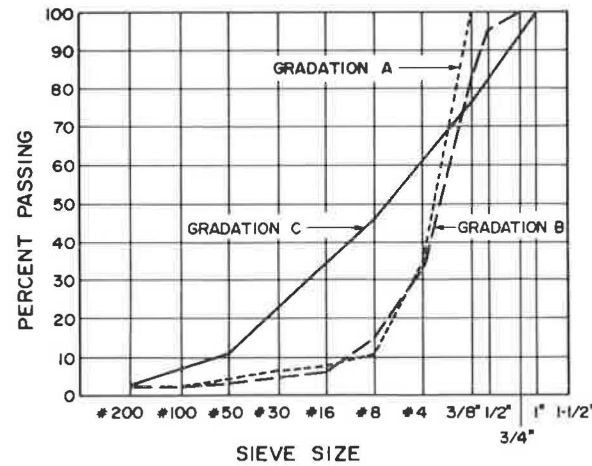

FIGURE 3 Aggregate gradations used in this study.

TABLE 1 SPECIFIC GRAVITIES AND ABSORPTION OF AGGREGATE GRADATIONS A, B, AND C

Gradation	Size[a]	G_{APP}	G_{SSD}	G_{OD}	P (%)
A	Coarse	2.729	2.688	2.665	0.86
	Fine	2.711	2.660	2.629	1.18
B	Coarse	2.735	2.676	2.642	1.30
	Fine	2.684	2.622	2.585	1.42
C	Coarse	2.712	2.661	2.631	1.13
	Fine	2.683	2.616	2.577	1.54

[a]Coarse is +No. 8; fine is –No. 8.

Asphalt Binder

AC-40 asphalt cement samples were obtained from the same source as the binder used in the field. Table 2 gives the asphalt binder characteristics.

Cores

Six 4-in.-diameter cores were obtained from the center of the outside lane of the existing porous pavement in order to compare their properties with those of laboratory-prepared samples. Dry ice was placed on top of the selected core location for approximately 15 min before drilling to stiffen the material during the coring operation. The cores were kept in a low-temperature-controlled room to prevent disintegration during the short storage time before they were trimmed to 2.5-in. thicknesses and tested.

Specimen Preparation

Marshall-size open-graded specimens were prepared according to Arizona Method 814 (*8*) using 950 g of aggregates blended to the specified gradations (A and B). The mixture was compacted at a temperature of 230 ± 5°F using the Marshall hand compactor and applying 75 blows on each side. The same compactive effort was used on the dense-graded specimens that were prepared according to the ASTM D 1559 procedure. Three replicate specimens were prepared for each combination of asphalt content and aggregate gradation for each test.

TABLE 2 ASPHALT BINDER PROPERTIES

Test	AASHTO Method	Test Results	ADOT Specification
Absolute viscosity at 140°F (poises)	T202	4004	3200–4800
Kinematic viscosity at 275°F (centistokes)	T201	327	300 min
Penetration at 77°F, 100 g, 5 sec	T49	44	40 min
Flash point, Penesky-Martin (°F)	T73	537	450 min
Absolute viscosity of aged residue (poises)	T202	10 197	20 000 max
Ductility at 77°F (centimeters), aged residue	T51	+145	75 min
Specific gravity	T228	1.023	

Laboratory Testing

The tests performed included

1. Density
   - Dense specimens: saturated surface dry method (ASTM D 2726).
   - Open-graded specimens: weight of the specimen in air divided by its volume as determined from physical dimensions (i.e., height and diameter).
2. Marshall test (ASTM D 1559).
3. Resilient modulus test at 41°F and 77°F (ASTM D 4123) with a pulse duration of 0.1 sec and a rest period of 2.9 sec. Poisson's ratios of 0.3 and 0.35 were assumed at the two temperatures, respectively.
4. Indirect tension test at 77°F (ASTM D 4123) with a rate of loading of 2 in./min. The Instron electrohydraulic closed-loop loading machine was used. The same specimens used in the resilient modulus test were used in the indirect tension test.
5. Constant head permeability test (*11*) (Figure 4).

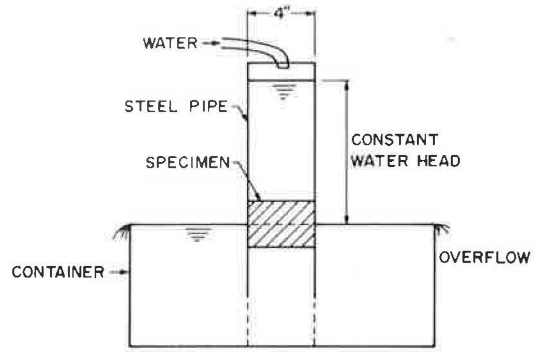

FIGURE 4 Constant head permeability apparatus.

RESULTS AND DISCUSSION

The results were statistically analyzed using the ANOVA technique at a significance level of 5 percent. A two-factor factorial design was employed for all response variables except the resilient modulus, which was analyzed as a three-factor factorial. The statistical analysis yielded the following results.

Density and Air Voids

The density of laboratory-prepared open-graded specimens ranged from 118.7 to 124.5 pcf with an average of 121.7 pcf. The average densities obtained for the different asphalt contents and aggregate gradations are given in Table 3. Both asphalt content and aggregate gradation significantly affected the compactibility of the mixture. In general, because of the high air voids content that characterizes the open-graded asphalt mixture, the added asphalt cement fills the voids and leads to higher densities.

TABLE 3 AVERAGE DENSITIES OF SPECIMENS INCLUDED IN THE STUDY

Asphalt Content (%)	Gradation A	Gradation B	Gradation C	Cores
4.0	119.2	122.8		
4.5	119.6	122.7		
5.0	120.6	123.6		
5.7	121.3	123.7	143.4	112.3

NOTE: Units are pounds per cubic foot.

The change in aggregate gradation from A to B yielded higher densities. Also, the cores showed a significant decrease in density compared with specimens prepared in the laboratory and containing similar material ingredients. It should be noted that a number of compaction techniques were used in the field and that the low densities observed in the cores may have been caused by the difficulty of compacting the mix in the field, especially at the high temperature encountered during construction, or by the lack of support of the subbase layer of cohesionless unbound aggregate.

The densities of the dense-graded specimens were, as expected, much higher than those of the open-graded specimens. Obviously, the larger fine aggregate fraction of the dense mixture, which results in a low air voids content, is the major cause of the higher densities.

The percentage of air voids of all laboratory-prepared open-graded specimens ranged between 17.8 and 23.7 percent with an average of 20.8 percent. Table 4 gives a summary of the average results for specimens prepared at various asphalt contents using different aggregate gradations. The percentage of air voids at the time of testing was significantly affected by the

TABLE 4 AVERAGE PERCENTAGE OF AIR VOIDS OF SPECIMENS INCLUDED IN THE STUDY

Asphalt Content (%)	Gradation A	B	C	Cores
4.0	23.4	20.9		
4.5	22.6	20.4		
5.0	21.3	19.2		
5.7	20.0	18.4	6.0	25.9

asphalt content and the aggregate gradation. In addition, the average percentage of air voids of specimens prepared with Gradation A was slightly higher than that of specimens prepared with Gradation B.

The low densities of the cores led to a higher air voids content than was found in laboratory-prepared specimens. Laboratory specimens containing similar material ingredients had air voids contents of 20.0 percent, which is significantly lower than the average air voids content of 25.9 percent of the cores. On the other hand, an average air voids content of 6.0 percent was obtained for dense-graded specimens; this is lower than that for open-graded specimens.

Marshall Stability and Flow

The stability and flow results for asphalt mixtures evaluated in this study are shown in Figures 5 and 6. The typical stability of laboratory-prepared open-graded specimens ranged between 575 and 975 lb with an average of 705 lb. Asphalt content and

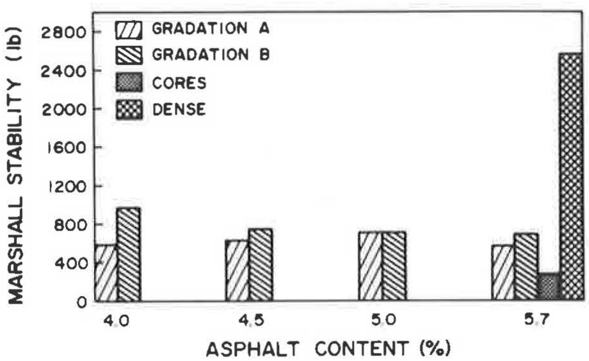

FIGURE 5 Effect of aggregate gradation and asphalt content on Marshall stability.

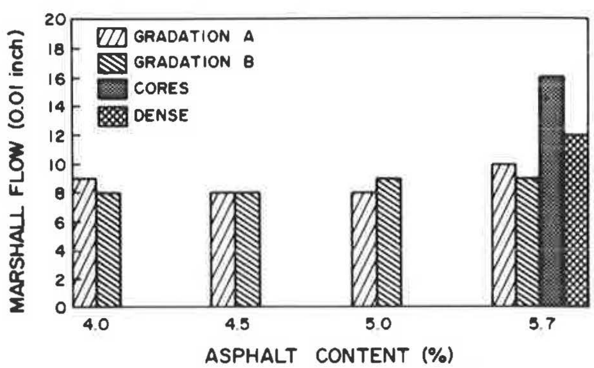

FIGURE 6 Effect of aggregate gradation and asphalt content on Marshall flow.

aggregate gradation as well as their interaction significantly affected the stability of the mixture.

The maximum stability value measured for the open-graded mixture was lower than that specified by most highway departments for dense-graded mixtures. However, it is not known if the same criterion should be applied to the open-graded mixture because no field performance data are available. Moreover, the average stability values of the open-graded cores were lower than those obtained for laboratory specimens prepared with the same material ingredients. The average stability of the cores was 270 lb, which is equal to 47 percent of the average stability of the laboratory specimens.

As expected, the average stability obtained for the dense-graded mixture (Gradation C) was significantly higher than for the open-graded mixture. The higher stability is caused by the larger fine aggregate fraction that provides a "choking" action between the larger aggregate particles. The average stability of the dense mixture was equal to 2,560 lb, which represents an increase of 265 percent over the overall average stability of the laboratory-prepared open-graded mixtures.

The typical flow values of the laboratory-prepared open-graded specimens ranged between 8 and 10. Figure 6 shows the average flow results of all asphaltic materials tested during this investigation. The narrow range of the flow indicates that neither gradation nor asphalt content had any practical effects on the flow of laboratory-prepared open-graded specimens. Further, the average flow obtained for the dense mixture was slightly higher than that obtained for the open-graded laboratory-prepared mixture. The flow values obtained for the cores had an average of 16, which is 60 percent greater than the average of laboratory specimens prepared with similar material components.

Resilient Modulus

Diametral resilient modulus at different temperatures is a measure of the stiffness and of the temperature susceptibility of an asphalt paving mixture. The trend toward rationally designing flexible pavements through numerical analysis of layered systems for strains, stresses, and deflections necessitates the use of the resilient modulus to characterize asphalt mixtures. In general, the resilient modulus is defined as the ratio of the applied stress to the recoverable or resilient strain after many repetitions when the load is applied in a pulsating form.

Figures 7 and 8 show the average instantaneous resilient modulus (E_{RI}) results determined for the laboratory-prepared specimens as well as the field cores at the two test temperatures.

The E_{RI} results of the laboratory-prepared open-graded specimens were significantly affected by test temperature, aggregate gradation, and asphalt content. As expected, an increase in temperature caused a decrease in E_{RI}-values because the higher temperature reduces the viscosity of the asphalt binder and therefore decreases the stiffness of the mixture. A reduction of 65 percent in the average E_{RI}-values was observed for both Gradations A and B when the testing temperature was increased from 41°F to 77°F.

At 77°F, a change in the aggregate gradation from A to B caused a 14 percent decrease in the average E_{RI}-value. Also, the change in asphalt content had no practical effect on the E_{RI}-

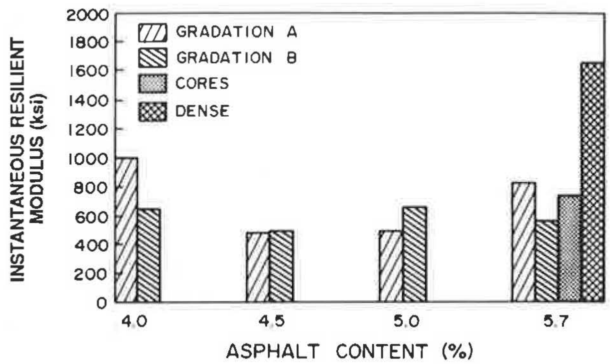

FIGURE 7 Effect of aggregate gradation and asphalt content on the instantaneous resilient modulus obtained at 77°F.

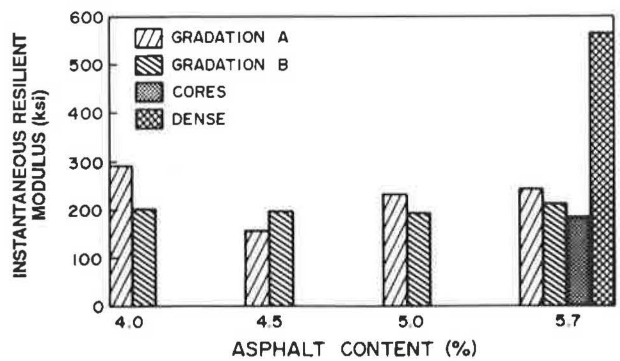

FIGURE 8 Effect of aggregate gradation and asphalt content on the instantaneous resilient modulus obtained at 41°F.

values measured at 77°F for specimens prepared with Gradation B. However, a change in asphalt content significantly affected the E_{RI} results of Gradation A. On the other hand, a change in aggregate gradation from A to B decreased the average E_{RI}-value by 19 percent from 705 to 595 ksi at a test temperature of 41°F.

The E_{RI} results of the open-graded cores were lower than those of the laboratory specimens prepared with similar material components. The decrease in the E_{RI} results is mostly attributed to the low core densities. Furthermore, the dense mixture exhibited E_{RI}-values that were much higher than those obtained for the open-graded specimens as shown in Figures 7 and 8.

The same factors and interaction of factors that affect the instantaneous resilient modulus results also influence the total resilient modulus (E_{RT}) results. Although the individual values might be different, the same trends observed for the E_{RI}-values are also observed for the E_{RT}-values.

Tensile Strength

Tensile strength is a measure of the maximum tensile stress an asphalt paving mixture can withstand. This parameter is related to thermal and shrinkage cracking resistance. In this study typical values of the tensile strength (S_T) of the laboratory-prepared open-graded specimens ranged between 100 and 120 psi with an average of 105 psi at a test temperature of 77°F. The average S_T-values obtained during this investigation are summarized in Figure 9. Neither aggregate gradation, asphalt content, nor the interaction of the two factors had any significant effect at a significance level of 0.05.

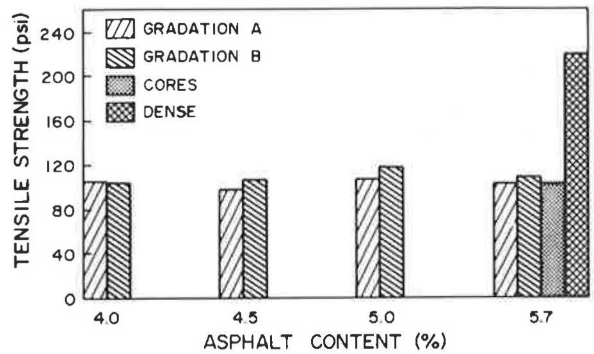

FIGURE 9 Average indirect tensile strength, obtained at 77°F, of specimens included in the study.

Unlike the other engineering properties investigated during this study, the average indirect tensile strength of the cores was similar to that of laboratory open-graded specimens prepared with similar material components. However, the variability of the S_T results for the cores was greater than that for the laboratory specimens because of the lower quality control that is usually experienced during field construction. The S_T results of the cores ranged between 85 and 130 psi with an average of 105 psi. In addition, the tensile strength of the dense-graded specimens was equal to 220 psi, which is high compared with an average of 105 psi for the open-graded specimens.

Coefficient of Permeability

The coefficient of permeability is an important parameter of open-graded asphalt mixtures. The coefficient of permeability determined in the laboratory may not match those expected in the field because of construction practices and poor quality control, operational problems, and maintenance activities. Tack coats, larger fine aggregate fraction than specified, and dust and patching are some of the problems that may be encountered in the field.

In this study, the coefficient of permeability (K) of laboratory-prepared specimens ranged between 321 and 621 ft/day with an average of 467 ft/day. Note that these values are much larger than the permeability value indicated in the design, which was 20 ft/day. The statistical results indicate that asphalt content, aggregate gradation, and their interaction largely affected the results. The average K-value of Gradation A was equal to 482 ft/day compared with 452 ft/day for Gradation B.

Asphalt content had a significant effect on the K results. Increasing the asphalt content reduced the permeability of the open-graded mixture (Figure 10). This effect can be explained by the fact that the excess asphalt is replacing the air voids and clogging some of the interconnected void channels.

No cores were tested for permeability by the authors. Data are available in the ADOT and the design company records about permeability of cores; however, these data were not available to the authors.

FIVE-MONTH FIELD EXPERIENCE

As of October 1986 (5 months after construction) the average rutting of the open-graded ADOT experimental section was about 0.2 in. in the wheel tracks and as high as 0.5 in. at some spots. The average rutting of the control (dense) section was 0.04 in. No cracking was observed in either the open-graded or the control sections. Also, minor roughness was noticed in the open-graded section. Noticeable improvement in drainage, which reduced glare and increased stripe visibility during rainfall, was observed in the open-graded section.

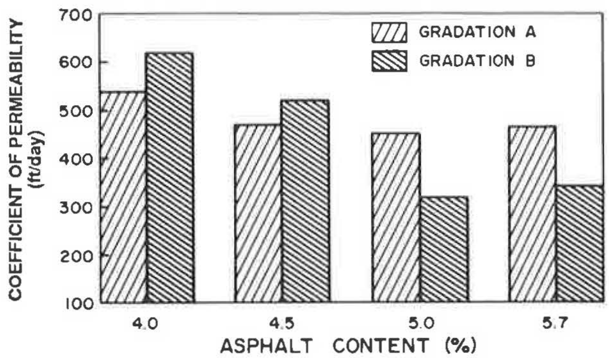

FIGURE 10 Effect of aggregate gradation and asphalt content on the coefficient of permeability of laboratory-prepared hot-mixed, open-graded asphalt mixture (note: 1 ft/day = 0.5 in./hr).

DETERMINATION OF LAYER THICKNESS EQUIVALENCY

The results of laboratory evaluation of the resilient modulus and tensile strength indicated a large difference between the stiffness of the open-graded asphalt mixture and that of the dense-graded mixture. The lower stiffness of the open-graded material means that higher stresses are transmitted to underlying layers. As a result, a greater structural thickness is required than for dense-graded pavements.

The experimental porous pavement section was designed using the AASHTO method for flexible pavements that requires a knowledge of the structural layer coefficient (a_1) of the hot-mixed, open-graded asphalt mixture. The a_1-value was selected between 0.4 and 0.44. This selection was based on recommendations made by Hicks et al. (*12*) for the cold-mixed, open-graded emulsion mixtures that were used under traffic and environmental conditions different from the ADOT project conditions.

In this study, the equal mechanistic response approach was used to evaluate the layer thickness equivalency (LTE) factor of the open-graded asphalt mixture (*13*), which can be further used to determine the structural layer coefficient, a_1. The maximum vertical deformation on top of the subgrade under a dual 4,500-lb wheel load was selected as the response parameter. Little and Epps (*13*) indicated that the vertical deformation on top of the subgrade is directly correlated with pavement performance, particularly in terms of riding quality and possibly rut depth. The multilayered elastic computer program ELSYM5 (*14*) was used in this study to model the pavement structure.

The LTE factor of the open-graded asphalt mixture was evaluated for the pavement structure shown in Figure 11. The structural cross section represents the porous pavement experimental test section. The maximum compressive vertical deformation on top of the subgrade was determined at different surface layer thicknesses of the open-graded and the dense-graded asphalt mixtures. The deformations were plotted versus the corresponding surface layer thicknesses of each mixture. Consequently, the thickness of the open-graded layer (H_1) and that of the dense-graded layer (H_2) required to obtain equal deformation on top of the subgrade were determined from these plots. The ratio of H_1 to H_2 was then computed. This ratio is equal to the LTE factor (*13*).

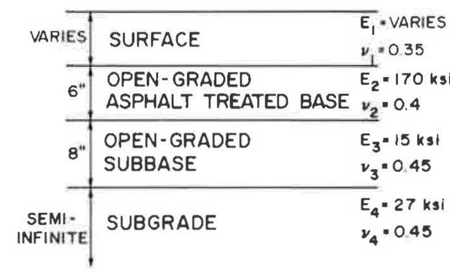

FIGURE 11 Pavement structure used in LTE computations.

The instantaneous resilient moduli of both hot-mixed, open-graded and dense-graded asphalt mixtures evaluated in the laboratory at temperatures of 41°F and 77°F were used to characterize the surface layers of the two pavement structures using the ELSYM5 computer program. The moduli of the base and subbase were estimated from the design charts produced by Van Til et al. (*15*). The modulus of the subgrade was backcalculated from the falling weight deflectometer data measured on the experimental and the control pavement structures. Typical Poisson's ratios of various materials were assumed. The moduli and Poisson's ratios of various layers are shown in Figure 11. It should be noted that the subgrade modulus is relatively large, which might be due to the inappropriate assumption of semi-infinite subgrade.

The computed LTE factors are given in Table 5. The overall LTE average of the cores was 1.7, which is much greater than 1.1 that was used during the design of the porous pavement. This indicates that the open-graded surface layer should have been 9.3 in. instead of the 6 in. used in the field. The overall LTE average of the laboratory mixture was 1.45, which requires a surface layer thickness of 7.9 in.

TABLE 5 AVERAGE LTE-VALUES OF OPEN-GRADED ASPHALT MIXTURE

Temperature (°F)	Based on Core Testing	Based on Laboratory-Prepared Specimens	Average
41	1.41	1.33	1.37
77	1.98	1.57	1.78
Average	1.70	1.45	1.57

Finally, the increase in temperature resulted in higher LTE factors. This was expected because the increase in temperature causes a large decrease in the modulus of the open-graded mix compared with the relatively small decrease in the modulus of the dense mix. This causes a large increase in stresses, strains, and deformations in the lower pavement layers under the open-graded surface layer.

It should be noted that the thickness requirements computed in this study were based on subgrade strain. However, rutting in the field may have resulted from several factors, and subgrade strain is only one of those factors.

CONCLUSIONS AND RECOMMENDATIONS

1. Core densities were much lower than the densities of laboratory specimens, which affected most of the properties evaluated in this study.

2. The average Marshall stability of the cores was equal to 270 lb compared with 575 lb for laboratory specimens. The Marshall flow decreased from 16 for the cores to 10 for the laboratory specimens.

3. The average instantaneous resilient modulus of the cores was equal to 745 and 185 ksi at test temperatures of 41°F and 77°F, respectively, compared with 830 and 245 ksi for the laboratory specimens prepared with similar ingredients. Similar trends were observed for the total resilient modulus.

4. Asphalt content and aggregate gradation had large effects on density, air voids, Marshall stability, resilient moduli, and coefficient of permeability. However, tensile strength was not greatly affected by these two factors.

5. The open-graded mixture was extremely sensitive to test temperature. The instantaneous and total resilient moduli significantly decreased with an increase in temperature. The open-graded mixture was unstable at high temperatures, which prevented the determination of the resilient modulus characteristics of the mixture at 104°F as recommended by ASTM D 4123.

6. The coefficient of permeability of all specimens evaluated ranged between 321 and 621 ft/day. It was significantly affected by asphalt content and aggregate gradation.

7. A large difference was observed between the properties of the dense-graded mixture and those of field and laboratory open-graded mixtures. Higher density, stability, tensile strength, and resilient moduli and lower air voids were obtained for the dense mixture.

8. The layer thickness equivalency factors indicate that 1.7 in. of the open-graded mixture is required to replace 1 in. of the dense mixture in the field. The factor could be reduced to 1.45 if construction practices were able to reproduce the material properties found in the laboratory.

On the basis of these laboratory measurements and theoretical analyses as well as observations made in the field at the site of the experimental porous pavement, the following conclusions are drawn:

1. The open-graded asphalt mixture appears to be capable of draining storm waters as indicated by its high coefficients of permeability.

2. The open-graded asphalt mixture is more susceptible to temperature than is dense-graded asphalt concrete. At high temperatures, the stability of asphalt mixtures is dependent mostly on aggregate interlock rather than on the binding ability of the asphalt binder because the increase in temperature reduces the viscosity of the binder. Aggregate interlock is far less available in open-graded asphalt mixtures than in dense mixtures because of the fewer points of contact between aggregate particles. Therefore the use of open-graded asphalt mixtures in pavement structural layers in hot climates, such as in Arizona desert areas, should be discouraged for roads that carry a high traffic volume and a high percentage of trucks.

3. The open-graded surface layer of the experimental porous pavement quite likely contributed to the rutting observed during construction especially given the high temperature of the pavement. This contribution was partly caused by the inability to obtain the same level of compaction in the field as that obtained in the laboratory. Furthermore, shear deformation may have occurred in the open-graded surface layer because of its low stability. On the other hand, the open-graded base and subbase layers of the porous pavement may have significantly contributed to the problem.

4. Because of the low resilient modulus of the open-graded asphalt mixture especially at high temperatures, its load-spreading capability is lower than that of the dense asphalt mixture. To decrease the stresses and deformations in the subgrade, thicker open-graded surface layers are required. However, the thicker open-graded surface layer may not guarantee lower susceptibility to rutting because of the potential of compaction and shear-induced strain within the surface layer itself.

5. If a permeable mix is a necessity, a mixture consisting of aggregates conforming to Gradation B and a 4.0 percent asphalt content by weight of aggregate is recommended for use under light or medium traffic in favorable climates.

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