Design, Construction, and Performance of Asphalt Friction Courses

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During 1969 to 1971, eight test pavements of open-graded asphalt friction courses were constructed in Pennsylvania. Details of design, construction, and performance of these pavements are discussed. Four test pavements incorporating two aggregate types and control sections of dense-graded bituminous surface were constructed in 1974 near Philadelphia. The asphalt friction courses were designed according to the Federal Highway Administration procedure modified in terms of asphalt mixing viscosities. The performance of the 1974 test pavements is evaluated every 6 months by obtaining skid test data at three speeds, by measuring air permeability, and by determining the average surface texture depths. Interim data obtained so far suggest that a minimum air void content of 25 percent is necessary to maintain the desired permeability that is lost in most pavements from traffic action and clogging by debris. A highly skid-resistant gravel aggregate was used for this project in the asphalt friction course and the dense-graded surface course. After 1½ years' service, the skid-speed gradient of both pavements is almost equal and approaches 0.45. In the case of dolomite aggregate (medium skid resistance), the asphalt friction course has a substantially lower speed gradient compared to the dense-graded surface course. These tests are being continued to study long-range performance and durability.

High-speed rubber-tired vehicles operating on wet pavements can experience a hazardous phenomenon known as hydroplaning. A layer of water on the pavement causes the tire to lose contact with the pavement surface. The result is the vehicle's loss of maneuverability and braking capability.

Obviously, we must devise some method to remove the water from the pavement surface. Open-graded asphalt friction courses (also called open-graded plant-mix seal coat and porous friction course, among others), which are high-void bituminous mixtures placed on existing pavement surfaces in thin layers [nominally 19 mm (¾ in)], have been used to drain surface water through their porous structures. In addition to reducing the risk of hydroplaning, asphalt friction courses are believed to have several other advantages (1), such as improved skid resistance at higher speeds during wet weather, minimized wheel path rutting, minimized splash and spray during wet weather, lowered highway noise levels, improved visibility of painted traffic markings, and retarded ice formation on the surface.

A survey of the literature (2,3,4,5,6,7,8,9) reveals that several agencies have used this type of asphalt surfacing, but with different mix compositions and mix design methods (Table 1). Evidently, this resulted in both success and failure in the construction and performance of the open-graded mixes, but the experience gained has helped develop suitable interim specifications and design methods for such applications. It is with this intent that the experience of the Pennsylvania Department of Transportation (PennDOT) with the design, construction, and performance of asphalt friction courses is being reported in this paper.

TEST PAVEMENTS, 1969 TO 1971

Eight separate projects (Table 2) were constructed in Pennsylvania between September 1969 and September 1971. In September 1969, 22.4 km (14 miles) of two-lane pavement were constructed and an additional 6.2 km (3.9 miles) in June 1970 in the north central region, and, in September 1971, 7.2 km (4.5 miles) were constructed in the same region and 2.4 km (1.5 miles) in south central Pennsylvania. This provided a total of 38.2 km (23.9 miles) for evaluation.

Design and Materials

The open-graded mixes first used in the four western states of Colorado, Wyoming, Utah, and New Mexico were also used in Pennsylvania (Table 1). Both limestone and gravel aggregates were used for comparison on projects 3 and 5; AC-20 asphalt cement was used on all projects. Initially, the asphalt content was established by calculating the percentage of asphalt as 1.5 Kc (surface capacity) plus 3.5.

The value of Kc was obtained by the CKE test using the coarse aggregate fraction and SAE 10 lubricating oil (1). Trial mixes with different percentages of asphalt were made and stored overnight at 140°F (60°C) in pans. We selected the mixes that met the following criteria.

Table 1. Comparison of mix gradations.

State	Gradation (% passing) 12.5 mm	9.5 mm	4.75 mm	2.36 mm	75 μm	Asphalt Content (%)
North Carolina	100	90 to 100	25 to 45	4 to 17[a]	0 to 2	6 to 10
Colorado, Wyoming, Utah, New Mexico	100	95 to 100	30 to 50	10 to 25	0 to 5	6 to 7
California, Arizona, Nevada, Hawaii	100	90 to 100	30 to 50	15 to 32	0 to 3	5 to 7
Louisiana	100	95 to 100	30 to 55	5 to 26[a]	0 to 6	4 to 10
Texas	100	90 to 100	40 to 60	9 to 20[a]	0 to 5	5 to 7.5
Virginia (1973)	100	84 to 100	10 to 40	0 to 10	0 to 2	6 to 12
FHWA recommendation (1974)	—	100	30 to 50	5 to 15	2 to 5	—

Note: 1 mm = 0.039 in and 1 μm = 0.0039 in.
[a]Sieve size converted from 2 mm (no. 10) to 2.36 mm (no. 8) for comparison.

Table 2. Test pavements, 1969 to 1971.

Project	County	Date Placed	ADT	Depth (mm)	Substrate Condition	Present Status
1	Centre	9/69	2 600	12.5	Fair, minimum cracking and rutting, slippery	Poor, 40% surface material lost from traffic wear; failure due to thin application; scheduled for resurfacing
2	Centre	9/69	9 400	12.5	Fair, slight wheel track rutting, slippery	Poor, 50% surface material lost from traffic wear; failure due to thin application; scheduled for resurfacing
3	Clearfield	9/69	6 000	12.5	Poor, heaved and sunken areas, wide transverse cracks	Resurfaced in 1973; failure due to poor pavement structure and thin application
4	McKean	9/69	2 650	12.5	Extremely poor, extensive cracking and rutting	Resurfaced in 1972; failure due to poor pavement structure and thin application
5	Centre	6/70	26 000	16.0	Good, slippery[a]	Good; in-service; original open surface texture kneaded and tightened by traffic
6	McKean	8/71	3 500	12.5	Fair, transverse and longitudinal cracks, raveling	Good; in-service; some reflective cracks present; slightly kneaded surface texture; 5% surface lost from raveling
7	Franklin	9/71	3 200	16.0	Good, slippery	Good; in-service; slightly kneaded surface texture
8	Mifflin	10/71	14 600	16.0	Good, slippery, some scattered cracks and rutting	Good; in-service; surface worn through to original surface in scattered areas; very tightly kneaded mat

Note: 1 mm = 0.039 in.
[a]Skid number 29.

1. A small but not excessive amount should drain to the bottom of the pan;
2. The mix should appear glossy rather than dull; and,
3. If a freshly prepared mix is molded into [102 by 102 by 16-mm (4 by 4 by $^5/_8$-in)] pats on the glass plate, the mix should exhibit a complete seal on the glass plate and open texture on the surface.

The composition of the mixes based on laboratory extractions is given elsewhere (10). The average percentage passing the 6.35-mm (no. 3) sieve was 18.

Construction Data and Procedure

The condition of the roadways prior to the application of the friction course was documented (10). A brief description is given in Table 2. In most cases RS-1 emulsified asphalt was applied at 0.23 L/m^2 (0.05 gal/yd^2) as a tack coat, which was often damaged by construction traffic. Mix temperatures ranged from 127 to 135°C (260 to 275°F). Although the mix design method allows some extra binder for flow-down during and immediately after placement to form a complete seal, such flow was not observed.

No serious problems were encountered during transport, placement, or compaction of these mixes. Compaction was accomplished with two to three passes of a 9-Mg (10-ton) steel-wheeled roller. Traffic permitted on the friction courses immediately after completion of rolling caused no damage.

Performance and Skid Data

The present status of the projects is described briefly in Table 2. The first four projects are of dubious experimental value, because the friction course was placed at a thickness of 13 mm ($^1/_2$ in) or less. This caused premature loss of aggregate and, consequently, early failure of the test sections. Failure resulted from the structurally unsound pavements underneath these applications. The raveling of the open-graded mix usually began near structural or reflective cracks.

It has been observed that debris and traffic action have closed up the voids in open-graded friction courses and that for all practical purposes these surfaces are impermeable. Although the friction courses in areas of low average daily traffic (ADT) volume have maintained good surface texture, those in areas of high traffic volume (12 000 to 24 000 ADT) have developed a tight, coarse texture similar to that of a dense-graded mix. The average percentage passing the 2.36-mm (no. 8) sieve in these mixes was 18, which should obviously be lowered if permeability is to be maintained as traffic becomes heavier.

The skid test data from these projects (Figure 1), with the exception of one carbonate aggregate source (project 8), show generally good to excellent results. Those projects using coarse gravel aggregate are consistently higher in skid resistance. The averages (total of eight projects) show gravel surfaces to be about 20 skid numbers higher than carbonate surfaces. For individual projects, where both aggregate types were used on the same site, the gravel surfaces are about 10 to 15 skid numbers higher.

It is evident from Figure 1 that initially these test pavement skid resistances were lower because of the presence of a thick asphalt film surrounding the aggregates at the surface. Skid resistance increased when aggregate microtexture was exposed by traffic wear.

All skid test data were obtained at 64 km/h (40 mph) on a one-wheel towed trailer as per ASTM test designation E-274.

TEST PAVEMENTS, 1974

Judging from experience gained from the 1969 to 1971 test pavements, we felt it was necessary to consider the following factors.

1. Gradation. We observed, as mentioned earlier, that the gradation should be made coarser to maintain permeability of the open-graded mixes. The amount of material passing the 2.36-mm (no. 8) sieve should be decreased.
2. Asphalt content. The percentage of asphalt had previously been selected by conducting a series of asphalt "drainage" tests on several trial mixtures made with various asphalt percentages. It was still possible that the mix could contain either too little asphalt, which could cause raveling, or too much, which could result in flushing. A more reliable method was needed.
3. Mix temperature. Mix temperatures were chosen arbitrarily. Logically, viscosity should be used in establishing mix temperatures.

The design procedure described by Smith, Rice, and Spelman (1) seemed to be reliable and logical. This method had been used successfully on several Federal Highway Aministration (FHWA) R&D demonstration projects. In the design procedure, the optimum content of fine aggregate is established by finding the void

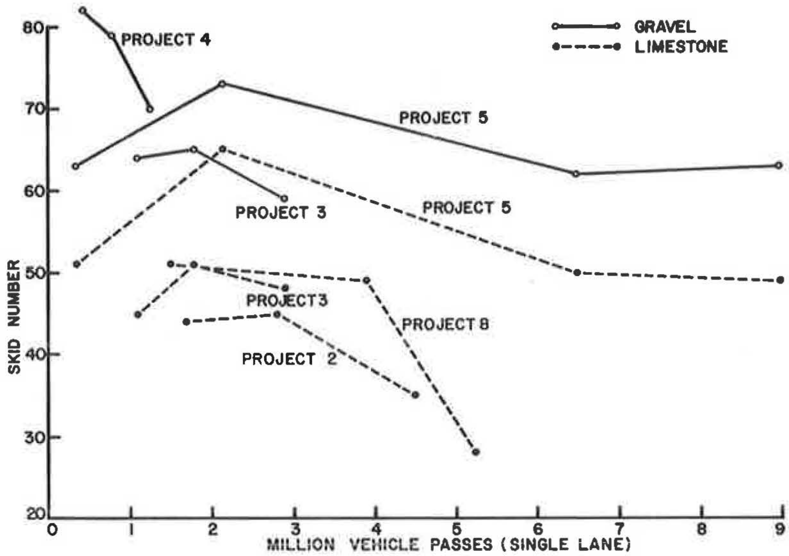


Figure 1. Pavement skid data, 1969 to 1971.

capacity of coarse aggregate and providing a minimum air void content of 15 percent. The asphalt content is determined from the surface capacity of the predominant aggregate size fraction. Optimum mixing temperature is based on asphalt viscosity.

Therefore 1974 test pavements of open-graded asphalt friction course were designed and placed according to the FHWA procedure. The project is located near Philadelphia on Route 252 (LR 144) in Delaware County (Figure 2). The roadway is 7.3 to 9.1 m (24 to 30 ft) wide and carries an ADT of 18 000. High traffic volume and heavy use of studded tires (35 percent during winter months) had badly worn the existing bituminous pavement, which was otherwise structurally sound with a minimum of cracking. Before paving, maintenance forces placed a thin leveling course in some areas of excessive rutting.

Design and Materials

The project included these four test sections (1 mm = 0.039 in) constructed in October 1974:

Section	Material	Aggregate	Thickness (mm)
Control	ID-2A wearing course	Gravel	38
Experimental	Asphalt friction course	Gravel	19
Control	ID-2A wearing course	Dolomite	38
Experimental	Asphalt friction course	Dolomite	19

Pennsylvania ID-2A is a dense-graded surface course mix that is widely used in the state and served here as a control for comparison purposes. Crushed gravel was used to provide a highly skid-resistant surface, and the dolomite aggregate was specified for medium skid resistance.

The mix designs for asphalt friction courses were prepared at PennDOT's Bureau of Materials, Testing, and Research (BMTR). The design data are given in the table below [1 mm = 0.039 in and 1°C = (1°F - 32)/1.8]. The mixes were designed to provide 15 percent air voids. The voids in mineral aggregate (VMA) ranged from 37.2 to 39.2 percent.

Test	Asphalt Friction Course Mix: Gravel	Asphalt Friction Course Mix: Dolomite
Coarse aggregate in blend, %	85	95
Fine aggregate in blend, %	15	5
Specific gravity of coarse aggregate	2.545	2.819
Specific gravity of fine aggregate	2.747	2.700
Specific gravity of 9.50 to 4.75 mm fraction	2.622	2.847
Unit weight (vibrated), PCF	96.5	110.3
Voids mineral aggregate, %	39.2	37.2
Optimum fine aggregate, %	16.4	13.4
Kc	1.60	1.40
AC = 2 Kc + 4.0	7.2	6.8
AC (corrected), aggregate basis, %	7.3	6.3
AC, mix basis, %	6.8	5.9
Optimum mix temperature, °C	110	112.8
Asphalt viscosity at the optimum mix temperature, CST	1700	1400

According to the FHWA procedure, the target mixing temperature lies in the range corresponding to asphalt cement viscosities of 7 to 9 m^2/S (700 to 900 centistokes). However, while designing these mixes we observed that the 7- to 9-m^2/S range resulted in too much drainage. The optimum mix temperatures yielding satisfactory drainage corresponded to asphalt cement viscosities of 14 and 17 m^2/S (1400 and 1700 centistokes) for dolomite and gravel, respectively. Several other designs by BMTR have confirmed that a higher range of asphalt viscosity is required.

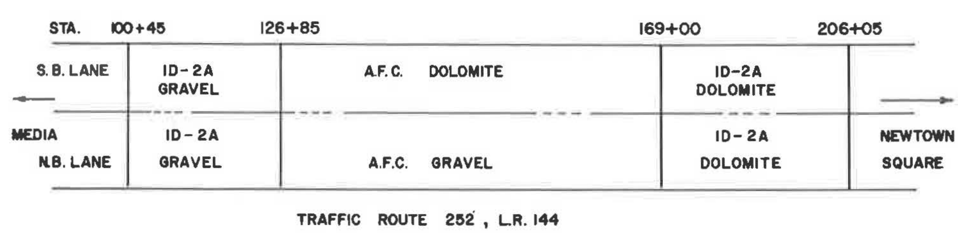


Figure 2. Pavement location map, 1974.

Construction Data and Procedure

Placement of the open-graded friction course mix went smoothly, and the mix that showed no signs of asphalt drainage or aggregate segregation had a somewhat rich appearance, as expected.

One or two passes of a steel-wheeled roller easily compacted the mix. Repeated rolling was of no value and even caused some degradation of the aggregate. The thickness of the compacted mat averaged 22 mm (⅞ in), slightly higher than the 19 mm (¾ in) specified.

Because of the delays between trucks arriving at the job site, the paver remained stationary for periods of time. As a result, the screed heaters, by lowering viscosity, caused the asphalt in the mat to drain, leaving dry-looking strips about 0.3 m (1 ft) wide across the lane. The condition did not seem to be detrimental, but it will be observed for any future effects.

The open-graded gravel mix appeared to be somewhat more open textured than the dolomite, as shown in Figure 3, which also shows the dense-graded ID-2A surface courses.

The mix designs and results of the plant and field test samples for the open-graded mixes are shown in Table 3. Samples of the open-graded gravel mix conformed well to the design. The plant sample of the open-graded dolomite mix was high on the 4.75-mm (no. 4) sieve, and the field sample was high on both that and the 2.36-mm (no. 8) sieve, as well as on asphalt content.

The mixes for the ID-2A wearing course also used the same gravel and dolomite aggregates. The material was designed to meet the requirements of PennDOT specifications.

Table 3. Mix design and test sample results for open-graded mixes.

	Percentage Passing						
		Gravel			Dolomite		
Item	Specification Limits	Design	Plant Sample	Job Sample	Design	Plant Sample	Job Sample
Sieve size							
9.5 mm	100	100	100	100	100	100	100
4.75 mm	30-50	31.3	42.4	41.8	34.9	53.9	51.9
2.36 mm	5-15	14.7	14.7	15.5	12.7	11.5	17.0
75 μm	2-5	1.9	3.5	2.8	3.6	3.2	4.6
Percentage of asphalt by weight of mix	6.0-8.0	6.8	6.8	6.8	5.9	5.9	6.4
Mixing temperature, °C	126.7 (max)	107.2-112.8	–	–	110-115.6	–	–

Note: 1 mm = 0.039 in; 1 μm = 0.0039 in; and t°C = (t°F - 32)/1.8.

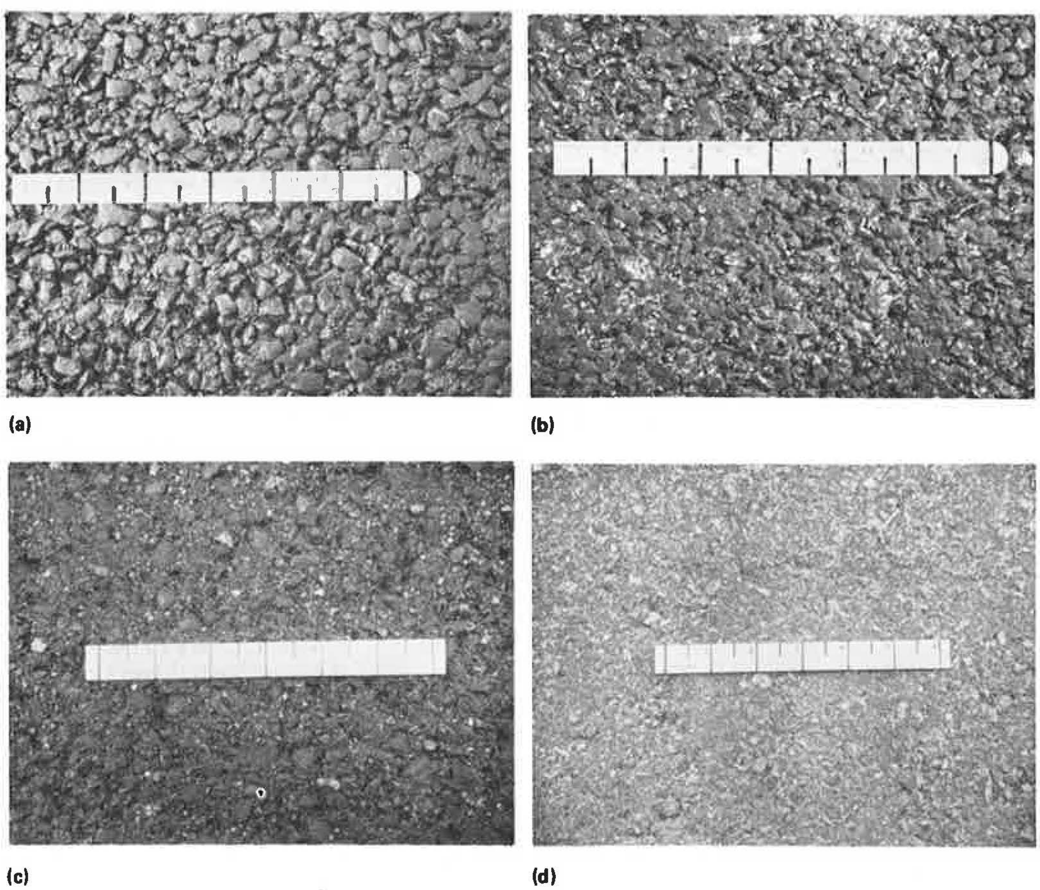


Figure 3. Comparison of mixes: (a) open-graded gravel, (b) open-graded dolomite, (c) ID-2A dense-graded gravel, and (d) ID-2A dense-graded dolomite.

Figure 4. Skid data on gravel mixes.

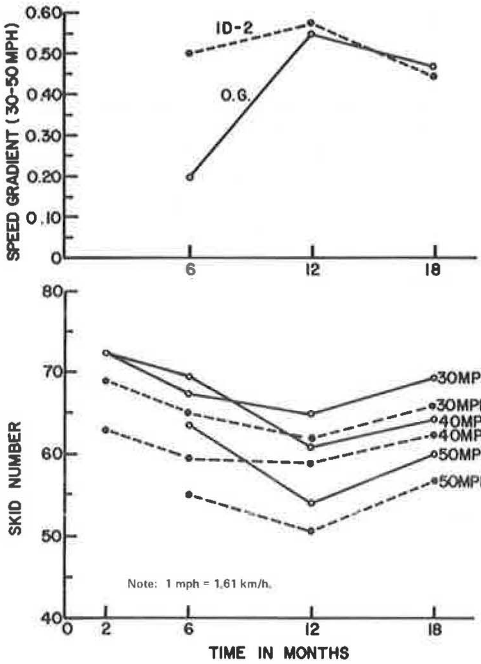
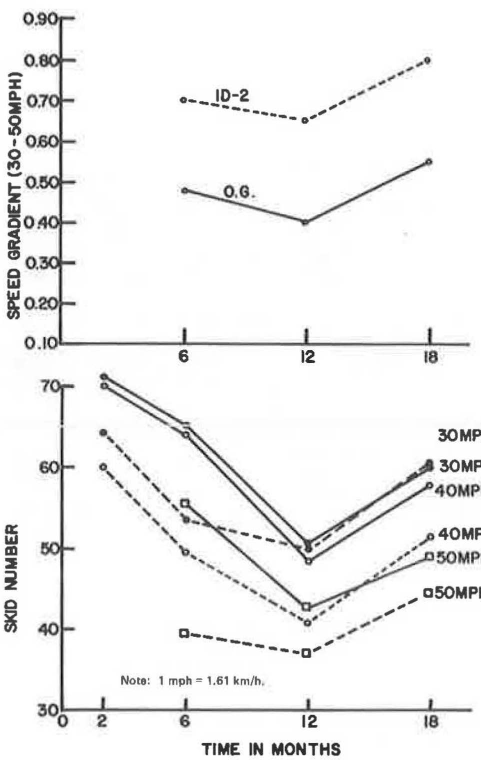


Figure 5. Skid data on dolomite mixes.



Performance Evaluation

The test pavements were constructed in October 1974 and have been evaluated at 6-month intervals since 2 months after placement. The evaluation includes judging visual appearance and measuring skid, permeability, and surface texture.

Table 4. Air permeability data.

Mix Type	Permeability (cm^3/min) At 20 Days	At 6 Months	At 12 Months	At 18 Months
Open-graded gravel				
W[a]	20 000+	1567	460	0
C[a]	20 000+	193	0	0
Open-graded dolomite				
W	8 600	57	560	78
C	6 100	740	1150	38
ID-2A gravel				
W	5	440	0	0
C	20	230	0	0
ID-2A dolomite				
W	114	13	0	0
C	269	4	0	0

Note: 1 cm^3 = 3.38 fluid oz.

[a]W = in the wheel track area and C = in the center of the lane.

Skid Testing

Tests were conducted at speeds of 48, 64, and 80 km/h (30, 40, and 50 mph) so that we could determine speed gradients. The skid level for each test section was taken as the average of 10 tests taken at two test sites. Skid test data for ID-2A gravel mix and open-graded gravel mix are shown in Figure 4. After 1½ years in service, the open-graded gravel mix is only two or three skid numbers higher than the ID-2A gravel mix. The speed gradient of both mixes is almost equal and approaches 0.45.

The open-graded mixes are generally thought to have lower speed gradients when compared with conventional dense-graded surface mixes. However, it is evident from this study that, if the aggregate possesses high skid resistance, this may not be generally true. If the aggregate—such as dolomite in this study—is not shown to be highly skid resistant, the open-graded mix has a substantially lower speed gradient (Figure 5). It seems that the microtexture predominates over the macrotexture when the mix contains highly skid-resistant aggregate, whereas macrotexture becomes a predominant factor when the mix contains relatively less skid-resistant aggregate. Continual evaluation of this project is necessary to drawing any firm conclusions.

Permeability

Permeability of the pavement surfaces has been measured periodically with the air permeability meter developed by the Pennsylvania State University (11). This device measures the rate of air flow in cubic centiliters per minute through the pavement at selected pressure differentials. Air pressure is applied to the surface of the pavement via a circular chamber sealed to the pavement with grease. Permeability readings are shown in Table 4.

Initially, the open-graded mixes had considerably higher permeability than the ID-2A dense-graded mixes. However, after 1½ years' service, the test pavements, compacted under traffic and clogged with debris, lost their permeability. Only the open-graded dolomite mix has so far retained some permeability, although it is insignificant and is approaching zero.

A minimum air void content of 15 percent was provided in the mix, according to the FHWA procedure, to ensure adequate subsurface water drainage, but apparently this minimum content will have to be increased to 25 percent, by reducing the fine aggregate content in the mix. This can have other implications.

A maximum amount of fine aggregate is desirable because it imparts a "chocking" action to the coarse aggregate particles and because it prevents mixture raveling (1). A possible compromise is to limit the amount of aggregate passing the 4.75-mm (no. 8) sieve to a maximum of 10 percent.

Surface Texture

Measurements of the pavement surface texture are being made with the sand track device developed by the Pennsylvania State University and modified by PennDOT (11). This device works first by placing the tester on a level area of the pavement. Then the hopper is filled with a specific amount of sand and, driven along by a spring motor, deposits a strip of sand on the pavement surface. The length of the strip will vary according to the roughness of the surface. The readings are then converted to the average texture depths shown in the following table (1 mm = 0.039 in). After 18 months in service, there is no significant difference between the open-graded mix and the ID-2A surface mix.

	Surface Texture Depth (mm)			
Mix Type	At 20 Days	At 6 Months	At 12 Months	At 18 Months
Open-graded gravel	0.0036	0.0046	0.0042	0.0029
Open-graded dolomite	0.0033	0.0030	0.0030	0.0026
ID-2A gravel	0.0025	0.0044	0.0043	0.0029
ID-2A dolomite	0.0017	0.0033	0.0018	0.0023

CONCLUSIONS AND RECOMMENDATIONS

Test Pavements, 1969 to 1971

We have been evaluating these pavements for 5 to 6 years and have made the following observations.

1. Open-graded mixes should not be placed less than 19 mm (3/4 in) thick.
2. Structurally unsound pavements cannot be corrected by applying an open-graded mix, which only results in premature failure of the application.
3. Debris and traffic action have closed up the voids in the open-graded mixes. In areas having an ADT over 12 000, the mixes developed a tight, coarse texture somewhat similar to that of a dense-graded mix. The average percentage of aggregate passing the 4.75-mm (no. 8) sieve in these mixes was 18, which is evidently excessive.
4. The open-graded pavement surfaces became impermeable, for all practical purposes, within 1 to 2 years.
5. Raveling usually began either where the mix was placed thinly over high spots or where there were edges or perimeters of cracks and joints in the pavement.
6. If properly laid, the average service life of an open-graded surface seems to be 5 to 6 years.

Test Pavements, 1974

Because the pavements have been evaluated for just 1½ years, this is only a progress report. We have made the following observations.

1. Optimum mix temperatures yielding satisfactory drainage corresponded to asphalt viscosities of 14 and 17 m^2/S (1400 and 1700 centistokes) respectively for dolomite and gravel aggregates. The range 7 to 8 m^2/S 700 to 900 centistokes recommended in the FHWA design procedure seems too low.
2. Open-graded mixes were designed, according to the FHWA design procedure, with 15 percent air voids to provide adequate permeability. However, after 1½ years' service the pavements lost their permeability from compacting under traffic and clogging of voids with debris. We estimate that a minimum air void content of 25 percent is necessary to maintaining permeability. The possible disadvantages of very high air void content (raveling, for instance) are not very clear.
3. After 1½ years in service, the open-graded gravel mix is only two to three skid numbers higher than the dense-graded ID-2A gravel mix. The speed gradient of 48 to 80 km/h (30 to 50 mph) for both mixes is almost equal and is approaching 0.45. This runs contrary to the general belief that the macrotexture of open-graded mixes gives them lower speed gradients than dense-graded mixes. It seems that microtexture predominates over macrotexture if a mix contains a highly skid-resistant aggregate, such as the gravel used in this project.
4. If the aggregate, such as the dolomite aggregate used in this project, is not highly skid resistant, the open-graded mix has a substantially lower speed gradient compared with the ID-2A dolomite mix after 1½ years in service. Macrotexture becomes a predominant factor if the mix contains relatively lower skid-resistant aggregate.

The evaluation of these test pavements will continue so that long-range performance and durability of the open-graded mixes can be compared with those of the dense-graded mixes.

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