EVALUATION OF PAVEMENT DRAINAGE SYSTEMS MADE OF LAYERS OF OPEN-GRADED BITUMINOUS AGGREGATE MIXTURES

Shiraz D. Tayabji and Ernest J. Barenberg, Department of Civil Engineering, University of Illinois

This study was aimed at evaluating the performance of pavement drainage systems in Illinois constructed with locally available aggregate sources. The study was limited to investigating the use of open-graded, hot-mixed bituminous aggregate mixtures in pavement drainage systems. A preliminary investigation was carried out in the laboratory to evaluate the permeability and the stability of the open-graded bituminous aggregate mixtures. Specimens were prepared according to the procedures in ASTM D1559. Permeability tests (in which a constant-head test that allowed the measurement of permeability at low heads was used) and stability tests were performed on the same specimen. From the results of the preliminary investigations, six test pavements incorporating different design concepts were tested at the University of Illinois test track. Dynamic loading was applied to the test pavements, and water was passed through the open-graded bituminous aggregate drainage layers to simulate surface and lateral infiltration. Permeability tests at a constant head were carried out regularly on the pavement test sections. The progress of rutting in the test pavements was also recorded. Results of these limited tests indicate that open-graded bituminous aggregate mixtures possess a high order of permeability and that care must be taken to prevent the migration of subgrade fines into these aggregate layers if satisfactory drainage is to be achieved. This paper discusses methods that can be used to ensure satisfactory performance of pavements made of open-graded aggregates.

•WATER is generally accepted as one of the most important factors affecting pavement performance. The primary approach to eliminating water in pavements has been to seal the pavement surface against water infiltration and, if conditions for seepage prevail, to provide sufficient drainage to handle the groundwater. Currently, pavement drainage systems are usually adopted from standards rather than rationally designed. This often leads to uneconomical or poorly performing drainage systems. Only recently, efforts are being made to better understand the concepts of pavement drainage. Cedergren and Lovering (1, 2) and Cedergren (3) have significantly contributed to an understanding of the design process of pavement drainage systems. Recently, several guidelines were published for the design of pavement drainage systems (4, 5), which incorporate asphalt-treated drainage layers made of open-graded aggregates.

Rationally designed pavement drainage systems should satisfy the following requirements. They should

1. Have adequate capacity to drain the pavement rapidly and should retain this capacity for some realistic service life,

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2. Be resistant to plugging, and
3. Possess sufficient stability so that the behavior of the drainage system itself does not interfere structurally with the behavior and the performance of the overall pavement system.

STUDY OBJECTIVES

The overall objective of this study was to evaluate the performance of pavement drainage systems that are used in Illinois and that are made of locally available aggregate sources. The study was limited to investigating the open-graded, hot-mixed bituminous aggregate mixtures (OGBAMs) used in the pavement drainage systems.

The primary factors investigated were

1. The permeability of OGBAMs,
2. The behavior of OGBAMs in pavement sections under load, and
3. The tendency of the drainage systems to plug and methods for reducing this tendency.

PRELIMINARY INVESTIGATIONS

General

Laboratory tests to evaluate the permeability and the stability of OGBAMs were designed to enable both characteristics to be measured on the same laboratory specimen. Laboratory specimens were prepared according to ASTM D 1559. Certain modifications were made in this procedure to allow for specific, unique characteristics of OGBAMs and their designated use. A constant-head permeameter was developed to measure the permeability of the prepared OGBAMs. The permeameter allows the measurement of permeability at very low heads and satisfies the conditions necessary for valid use of Darcy's law:

1. Laminar flow,
2. Steady state of flow,
3. The 100 percent saturation of the porous material, and
4. No change in volume during the test.

According to Darcy's law

$$Q = \overset{k}{K}iA \qquad (1)$$

or

$$k = Q/iA = \frac{Q \times L}{\Delta h \times A} \qquad (2)$$

where

Q = discharge per unit time (cm^3/s);
k = coefficient of permeability (hydraulic conductivity), length per unit time (cm/s);
i = hydraulic gradient (dimensionless);
A = cross-sectional area of specimen (cm^2);

L = length of specimen (cm); and
Δh = head causing the flow of water through the specimen (cm).

Test Criteria

Because of the open-graded nature of OGBAMs, permeability had to be measured at very low heads (3, 6). This requirement is based on the assumption in Darcy's law that the inertial force is negligible compared with the viscous force. For this investigation, a head differential of approximately $\frac{1}{16}$ in. (1.6 mm) was used. This corresponds to the hydraulic gradient of 2.5 percent for a specimen 2.5 in. (6.35 cm) high and agrees with the transverse pavement slopes used in practice.

Initial tests showed that permeability was inversely proportional to the compaction effort used in preparing the specimens. Excessively high compaction efforts caused particle breakdown and concomitant changes in particle gradation and, thus, a reduction in the volume of voids in the specimen. During the initial testing, 35 blows with a 10-lb (4.54-kg) mass dropped from a height of 18 in. (45.7 cm) on each face of Marshall specimens produced reasonable densities with a minimum of particle fracture. Therefore, this compactive effort was used throughout the laboratory testing program.

The Marshall method requires the immersion of specimens in water at 140 F ± 1.8 F (60 C ± 0.8 C) for 30 to 40 min before the stability test. Initial tests showed that this was too severe for OGBAMs. In that the drainage layer would be at least 6 in. (15.2 cm) below the surface of the pavement, it was felt that the requirement of 140 F (60 C) would be too severe and unrealistic when compared with actual environmental conditions. According to Straub et al. (7), the temperature observed over 1 year in the model test pavement of dense-graded bituminous mix never exceeded 100 F (37.8 C) at 8 in. (20.3 cm) or more depth and reached about 100 F (37.8 C) at 6 in. (15.2 cm) depth approximately 2 percent of the time. Thus, the specimens were immersed in the water bath at 100 F ± 1.8 F (37.8 C ± 0.8 C) for 30 to 40 min before the stability test. Three specimens were tested for each set to evaluate the variables of aggregate type, aggregate gradation, and asphalt content.

Results of Preliminary Investigations

Aggregate gradations meeting the specifications of Illinois Department of Transportation, CA-7, CA-8, CA-11, CA-13, and CA-15, were evaluated for permeability and stability as was an aggregate gradation recommended for a drainage blanket by the Federal Highway Administration (4). Gradations of the aggregates evaluated are given in Table 1.

Both crushed stone and gravel aggregates were evaluated. The A penetration-grade asphalt cement was used that had a penetration range from 85 to 100.

Results from the evaluation tests for the crushed-stone aggregates are given in Table 1, and those for the gravel aggregates are given in Table 2. All mixes tested had permeabilities in the range of 3,000 to 8,000 ft/day (1.06 to 2.82 cm/s). The Marshall stability values [100 F (37.8 C)] for the crushed-stone aggregates ranged from about 600 to 1,000 lbf (2669 to 4448 N), and the gravel aggregates had stability values ranging from about 300 to 450 lbf (1334 to 2002 N).

Recommended Test Sections

After the results of the preliminary investigations and the availability of construction materials in Illinois were evaluated, it was decided to use open-graded materials having gradations corresponding to Illinois Department of Transportation specifications CA-7 and CA-14.

Table 1. Results of material evaluation of crushed-stone aggregate.

Item	Specification										
	CA-7	CA-8A	CA-8B	CA-8A	CA-11	CA-13A	CA-13B	CA-15A	CA-15B	CA-15A	U.S. DOT
Aggregate gradation, percent passing sieve size											
3/4 in.	100	100	100	100	100	100	100	100	100	100	100
1/2 in.	60	45	65	45	55	100	95	100	100	100	72
3/8 in.	—	—	—	—	—	—	—	90	60	90	—
No. 4	10	5	15	5	10	50	20	15	0	15	0
No. 16	0	0	0	0	0	0	0	0	0	0	0
Asphalt content, percent	2	2	2	1.5	2	2	2	2	2	1.5	2
Average bulk specific gravity	1.89	1.88	1.93	1.88	1.85	1.87	1.89	1.83	1.83	1.86	1.86
Coefficient of permeability, ft/day	3200 to 4100	6600 to 8100	3600 to 4300	4700 to 6600	4300 to 5200	2600 to 3500	2800 to 3300	4000 to 5000	5500 to 6000	3300 to 3900	4900 to 7700
Average Marshall stability, lbf	777	851	806	611	824	806	1000	660	725	612	818

Note: 1 ft = 0.3048 m. 1 lbf = 4.448 N.

Table 2. Results of material evaluation of Pontiac gravel.

Item	Specification		
	CA-6A	CA-15A	U.S. DOT
Aggregate gradation, percent passing sieve size			
3/4 in.	100	100	100
1/2 in.	45	100	72
3/8 in.	—	90	—
No. 4	5	15	0
No. 16	0	0	0
Asphalt content, percent	2	2	2
Average bulk specific gravity	1.82	1.80	1.77
Coefficient of permeability, ft/day	5100 to 6500	3500 to 4900	6100 to 7900
Average Marshall stability, lbf	386	456	328

Note: 1 ft = 0.3048 m. 1 lbf = 4.448 N.

Figure 1. Layout of test track.

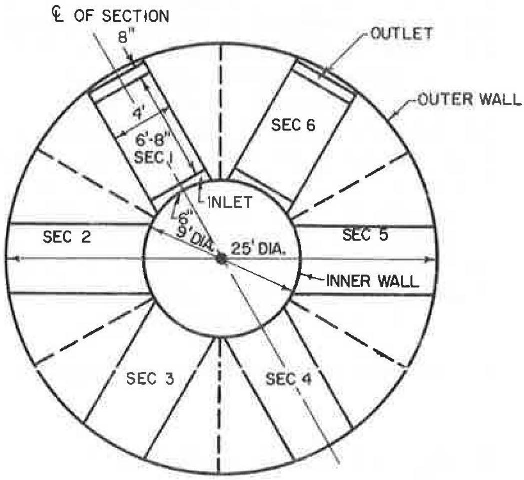


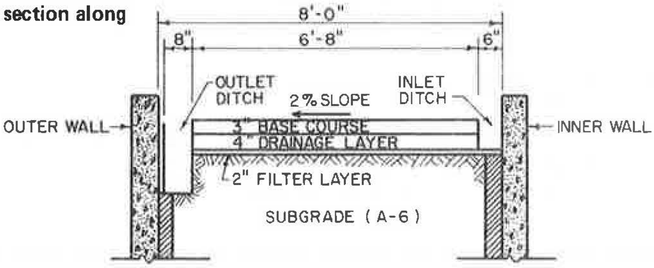
Table 3. Analysis of pavements selected for test sections.

Item	Test Sections					
	1	2	3	4	5	6
Surface course thickness, in.	3	3	3	3	3	3
OGBAM						
Aggregate type	CA-7	CA-7[a]	CA-7	CA-14	CA-7	CA-14
Thickness[b], in.	4	4	4	4	4	4
Sand layer thickness[b], in.	—	—	—	—	2	—
Lime-modified clay layer thickness[b], in.	2.5	—	—	—	—	2.5

Note: 1 in. = 2.54 cm.

[a]The OGBAM layer is to be placed over a filter cloth placed on the subgrade.
[b]These measurements are nominal.

Figure 2. Cross section of test section along centerline.



EXPERIMENTAL DESIGN

Test Pavement and Track Layout

The physical characteristics and use of the University of Illinois test track are well-documented in reports by Ahlberg and Barenberg (8) and Barenberg and Thompson (9). In summary, the circular track has an inside diameter of about 9 ft (2.74 m), an outside diameter of approximately 25 ft (7.62 m), and a pavement width of 8 ft (2.44 m). The center of the wheel path has a diameter of 16 ft (4.88 m), and this places it 3.5 ft (1.07 m) from the inside edge and 4.5 ft (1.37 m) from the outside edge of the test pavements. The test pavements rest on a prepared subgrade having a minimum thickness of 3 ft (0.91 m). Because of the physical limitations, the maximum number of test pavements considered practical in one test set is six; for this study, six test sections were chosen. The layout of the six test sections is shown in Figure 1. The pavement systems selected for the six test sections are given in Table 3.

Lime-modified clay layers in sections 1 and 6, a sand layer in section 5, and a filter cloth in section 2 were used to evaluate the functional characteristics of these materials. Sections 3 and 4, in which the drainage layer was laid directly on the subgrade, were used as control sections. All layers were designed to have a transverse slope of 2 percent. A transverse cross section along the centerline of a typical test section is shown in Figure 2.

Materials Used

The materials gradations used in the test track pavements are given in Table 4. Properties of the subgrade are given in Table 5. The physical characteristics of the bituminous aggregate mixtures obtained by using crushed stone are given in Table 6. High-quality, low-permeability asphalt concrete obtained from a local supplier was used in the surface course and placed between the test sections as transitions to ensure no lateral movements of water from one drainage layer to another.

Torpedo sand was tested as a filter layer but failed to satisfy the criteria to prevent clogging of the sand level by the subgrade. However, the satisfaction of this criterion was not relevant for this study, for only surface water drainage was under investigation.

Construction of Test Sections

The subgrade soil, which was already in place in the test pit, was removed to about 1 ft (0.3 m) below the designed level of the subgrade, was partially dried, brought to about optimum moisture content, and pulverized with a soil tiller. Lifts about 4-in.-thick (10-cm) were compacted around the entire track by a J-ram impact tamper.

A 2-in. (5-cm) layer of lime-clay mixture was placed in sections 1 and 6. A silty clay soil (Goose Lake clay) and 2 percent lime were mixed in the pug mill with enough water added to bring the materials up to optimum moisture content (13.0 percent) as determined by AASHO T-99. The mixture was placed in a single, 2-in. (5-cm) lift and was compacted to the desired density by using the J-ram tamper. The lime-clay was allowed to cure for 3 days at room temperature before the OGBAM layer was placed. In section 5, torpedo sand was placed, compacted, and brought to the desired level just before the OGBAM was placed.

Catch basins of galvanized sheet iron were placed adjacent to the outside wall in each section. Pie-shaped layers of dense-graded, hot-mixed asphalt concrete mixtures were placed between each drainage test section to provide impermeable barriers between the drainage sections.

The OGBAM layers were then placed between the impermeable pie-shaped sections. A filter cloth, Mirafi 140, was placed over the subgrade in section 2 before the OGBAM was placed. The OGBAMs were prepared in-house by using a Barber-Greene

Table 4. Aggregate gradation of materials used in test sections.

	Percent Passing					
	CA-7		CA-14			
Sieve Size	Tuscola Stone	Illinois DOT Specimen	Fairmount Stone	Illinois DOT Specimen	Torpedo Sand	Subgrade
1½ in.	–	100	–	–	–	
1 in.	100	90 to 100	–	–	–	
¾ in.	92.5	–	100	–	–	
½ in.	59.7	30 to 60	88.8	80 to 100	100	
⅜ in.	35.7	–	45.7	25 to 65	99.9	100
No. 4	11.5	0 to 10	4.2	0 to 6	96.9	98
No. 16	1.3	–	0.9	–	77.1	–
No. 30	–	–	–	–	54.5	–
No. 40	–	–	–	–	–	92
No. 50	–	–	–	–	9.1	–
No. 100	–	–	–	–	–	85
No. 200	–	–	–	–	1.0	79
0.02 mm	–	–	–	–	–	61
0.005 mm	–	–	–	–	–	39
0.002 mm	–	–	–	–	–	27

Table 5. Physical characteristics of subgrade.

Characteristic	AASHO Designation	Value
AASHO classification		A-6(8)
Optimum moisture content, percent	T 99-57	13.0
Maximum dry density, pcf	T 99-57	120
Liquid limit, percent	T 89-54	25
Plastic limit, percent	T 90-54	14
Plasticity index, percent	T 91-54	11

Note: 1 pcf = 16.02 kg/m³.

Table 6. Physical characteristics of drainage materials.

	Average Values	
Characteristic	Tuscola Stone[a] (CA-7)	Fairmount Stone[b] (CA-14)
Marshall specimen, 30 blows/face		
Bulk specific gravity	1.91	1.84
Stability, lbf	1570	1086
Flow, (× 0.01), in.	10	10
Coefficient of permeability, ft/day	8800 to 11,600	9300 to 9900
Marshall specimen, 40 blows/face		
Bulk specific gravity	1.95	1.89
Stability, lbf	1835	1294
Flow, (× 0.01), in.	11	12
Coefficient of permeability, ft/day	6200 to 6700	5900 to 7200
Marshall specimen, 50 blows/face		
Bulk specific gravity	1.95	1.91
Stability, lbf	1737	1550
Flow, (× 0.01), in.	10	9
Coefficient of permeability, ft/day	4200 to 5500	5600 to 6200

Note: Two specimens for each set were prepared. 1 lbf = 4.448 N. 1 in. = 2.54 cm. 1 ft = 0.3048 m.

[a]From the batch used for section 5 (asphalt content = 2.33 percent).
[b]From the batch used for section 6 (asphalt content = 2.00 percent).

Table 7. In situ properties of materials.

	Sections					
Characteristic	1	2	3	4	5	6
Subgrade						
Dry density, pcf	134.8	127.3	130.2	124.7	130.9	130.1
Percentage of standard	103.6	97.9	100.2	95.9	100.7	100.1
Moisture content, percent	10.0	11.7	11.8	10.4	10.7	10.2
Lime-clay layer						
Lime used, percent	2	–	–	–	–	2
Dry density, pcf	107.2	–	–	–	–	107.4
Percentage of standard	91.5[a]	–	–	–	–	91.7[a]
Moisture content, percent	13.3	–	–	–	–	13.7
Drainage layer						
Bulk specific gravity	1.80	–	174	1.75	1.82	1.76
Marshall stability, lbf	387	–	–	528	458	546
Flow, (× 0.01), in.	12	–	–	14	14	16
Asphalt used, percent	2.33	2.33	2.00	2.00	2.33	2.00
Surface layer						
Bulk specific gravity	2.37	2.33	2.32			
Marshall stability, lbf	1802	1304	1492			
Flow, (×0.01), in.	16	16	13			

Note: 1 pcf = 16.02 kg/m³. 1 lbf = 4.448 N. 1 in. = 2.54 cm.

[a]The layers were compacted further with the J-ram after the tests.

Mixall with a drum dryer in batches of about 300 lb (136 kg). The OGBAMs were compacted with the vibrating plate compactor and then were placed in single lifts approximately 4 in. (10 cm) thick. Because of the open texture of the mixtures, compaction effort was controlled to provide optimum density with a minimum fracturing of particles. Four-in.-diameter (10-cm) core samples were taken from each section, except for section 2, in which the OGBAM was laid over the filter cloth. The cores were tested for specific gravity and stability (by using the modified version of ASTM D1559 as described earlier). A 3-in. (7.6-cm) course of dense-graded, high-quality asphalt concrete (which was obtained from a local supplier and which met the Illinois Division of Highways requirements for a high-quality surface course) was placed over the OGBAM and compacted by using the vibrating plate compactor.

Table 7 shows the in situ properties of the materials used. The as-constructed geometrical details of the test sections are given in Table 8. Figure 3 shows the as-constructed test sections.

Test Concepts

Test sections were designed for the water to flow transversely through the drainage layers as shown in Figure 2. The drainage test was designed so that the coefficient of permeability could be obtained by the use of Darcy's equation (Eqs. 1 and 2).

The level of water at the inlet end was kept constant at the interface of the drainage layer and the surface course. This ensured constant flow of water under a constant head. For simplicity of calculations, the following assumptions were made:

1. All head loss was due to flow through the drainage layer,
2. The entire cross section of the drainage layer along the full width of the test section was used for the flow,
3. The hydraulic gradient for the flow was equal to the average gradient or slope of the layer on which the drainage layer was placed,
4. Flow was laminar, and
5. No volume change occurred during the tests.

The water passing through the drainage layer flowed into a collection basin (Fig. 2) and was pumped out continuously during testing. A water meter attached to the pump measured the quantity of water pumped. For measurement of permeability, the flow of water was measured over a period of 10 min. For the first 50,000 load applications, no wheel loads were applied while drainage tests were being conducted. After the first 50,000 applications, continuous moving wheel loading was maintained simultaneously with drainage tests. So that rainfall conditions could be simulated, water was also passed during the interval between the drainability tests for 30 and 60 min per section, and continuous wheel loads were applied. Turbidity of the discharged water was observed for every passage of water so that the severity of infiltration of fines could be evaluated. The time for the flow of water to emerge at the outlet ditch and the time for flow to stop at the end of the test were also noted. In some of the initial tests, after the flow of water had become steady, liquid dye was introduced at the inlet end, and the time taken for the dye to appear at the outlet was measured. This was discontinued after 50,000 load applications. Surface levels and rut depths were measured regularly to evaluate the distress in the test sections.

Dynamic loads were applied to the test sections by a loading frame (9, Fig. 3). Ballast was added to the loading frame to bring its effective mass to about 6,400 lb (2900 kg), i.e., 3,200 lb (1450 kg) per wheel. The loading frame rides on 8.25 × 20 ten-ply truck tires inflated to 80 psi (552 kPa). The speed of the wheels during loading was kept at about 7 to 8 mph (11 to 13 km/h) for most of the experiment. The rate of application was about 25/min. All wheel loads were normally distributed over a wheel path about 30 in. (76 cm) wide.

Table 8. As-constructed geometric details of test sections.

Item	Sections 1	2	3	4	5	6
Thickness, in.						
Lime-clay layer	2.2	–	–	–	–	2.6
Sand layer	–	–	–	–	1.7	–
OGBAM drainage layer	4.0	4.1	3.7	4.3	3.9	4.0
Surface course	2.8	2.8	3.2	2.6	2.8	3.0
Cross-sectional area of drainage layer						
Average, ft^2	1.31	1.33	1.23	1.39	1.30	1.30
Average gradient of base of drainage layer, percent	1.6	1.4	1.7	2.1	2.1	1.9

Note: 1 in. = 2.54 cm. 1 ft^2 = 0.09 m^2. Average width of section = 6.40 ft (19.51 m); length of section = 4.0 ft (12.2 m).

Figure 3. As-constructed test track.

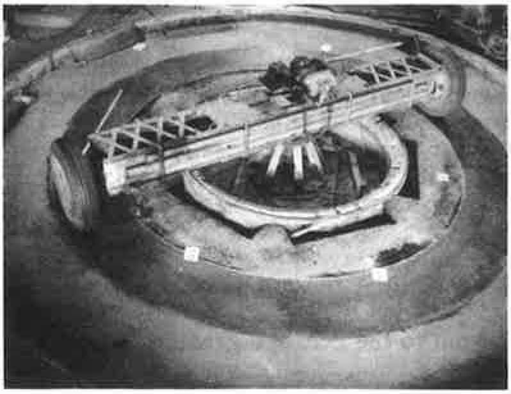


Table 9. Water passed through test sections during drainage tests.

Load Applications	Discharge at Outlet End by Section (ft^3/min) 1	2	3	4	5	6	Total Duration (min)
224	0.523 A	0.571 A	0.566 A	0.604 A	0.377 A	0.566 A	10
4,040	0.433 A	0.447 A	0.427 A	0.457 A	0.311 A	0.442 A	10
8,200	0.370 A	0.411 A	0.343 A	0.406 A	0.261 A	0.390 A	10
50,000	0.284 A	0.279 A	0.235 A	0.329 A	0.237 A	0.343 A	10
53,000[a]	0.284 A	0.290 D	0.307 C	0.330 B	0.245 A	0.346 A	10
60,000[a]	0.213 A	0.228 D	0.175 C	0.245 B	0.162 A	0.293 A	60
71,000[a]	0.271 A	0.276 E	0.294 D	0.314 C	0.227 A	0.354 A	10
101,000[a]	0.231 A	0.235 E	0.206 D	0.275 C	0.217 A	0.280 A	10
118,900	0.230 A	0.102 B[b]	0.186 A	0.244 A	0.225 A	0.322 A	10
130,000[a]	0.266 A	–	0.171 D	0.238 C	0.182 A	0.222 A	30
144,000[a]	0.222 A	–	0.192 E	0.270 C	0.230 A	0.267 A	30
148,000[a]	0.213 A	–	0.159 E	0.254 A[bc]	0.227 A	0.283 A	10
150,000[a]	0.166 A	–	0.159 E	–	0.205 A	0.232 A	30
164,000[a]	0.240 B	–	0.184 E	–	0.189 A	0.222 A	30
200,000[a]	0.237 B	–	0.129 E	–	0.212 A	0.203 A	30
210,000[a]	0.183 B	–	0.146 E	–	0.189 A	0.210 A	30
233,000[a]	0.168 C	–	0.085 E	–	0.266 A	0.285 B	10
246,074	0.140 B	–	0.059 C	–	0.222 A	0.281 B	10

Note: Turbidity scales for discharge water: A = clear, B = almost clear, C = slightly dirty, D = dirty, and E = very dirty. 1 ft^3/min = 0.0005 m^3/s.

[a]Application of loads during drainage test.

[b]Test conducted before removal of test section.

[c]Water passed through section 4 without load application.

TEST RESULTS

Table 9 gives the records of water that passed through the test sections during the drainage tests. From these data, the coefficients of permeability were calculated for each section by using Eq. 2. These results are given in Table 10. For the calculations of the coefficient of permeability, it was also assumed that the area of the cross section and the average transverse gradient of the drainage layer remained constant throughout the duration of the test. The temperature at which the permeability tests were conducted ranged from 70 F to 80 F (21 C to 27 C).

Section 1

Section 1 was made of an asphalt concrete surface, an OGBAM (CA-7) drainage layer, and a 2.2-in. (5.6-cm) lime-clay mixture layer placed over the subgrade.

The drainage trend, i.e., the change in the drainage of the OGBAM (in terms of rate of discharge and coefficient of permeability, k) with respect to the number of load applications, is shown in Figure 4. The coefficient of permeability of the drainage layer decreased by almost half from the initial value of 37,900 ft/day (13.4 cm/s) to 20,600 ft/day (7.27 cm/s) after 50,000 load applications. The coefficient of permeability stabilized at about 17,000 ft/day (6.0 cm/s) and then started decreasing at an increasing rate after 200,000 load applications to reach a final value of 10,000 ft/day (3.5 cm/s) at 246,074 load applications. As can be seen from Table 9, clear water was discharged up to 150,000 load applications. Up to 230,000, the turbidity of the water remained at almost the clear water level, and, just before the end of the testing program, the turbidity changed to the slightly dirty water level. The turbidity of the discharged water is shown in Figure 5 at 100,000 load applications.

Little rutting occurred in the lime-clay layer. Some consolidation occurred in the surface course and the OGBAM drainage layer.

When the section was opened up at the end of the testing program, the OGBAM matrix had loosened in the region of the wheel path and the particles had been covered with infiltrated fines from the lime-clay mixture. The OGBAM had penetrated into the lime-clay mixture layer to a depth of about ½ in. (13 mm).

Section 2

Section 2 was made of an asphalt concrete surface course and an OGBAM (CA-7) drainage layer placed over a filter cloth directly on the subgrade.

The drainage trend of the drainage layer is shown in Figure 4. The coefficient of permeability of the drainage layer decreased by almost half from an initial value of 46,200 ft/day (16.3 cm/s) to 22,600 ft/day (7.98 cm/s) after 50,000 load applications. The drainage performance of this section deteriorated rapidly with the continuous application of load and water, and dirty water was discharged almost immediately. The coefficient of permeability dropped to 8,300 ft/day (2.93 cm/s), and the turbidity of water increased rapidly to the very dirty water level (Table 9). Figure 5 shows the extent of the washing of the subgrade fines at 100,000 applications.

After 50,000 load applications, rutting progressed at an increasing rate and was 2.5 in. (6.4 cm) deep at the point of maximum rutting after 118,900 load applications. Transient deflections under wheel load became apparent to the observer at about 60,000 load applications, and the magnitude of these deflections increased when there was further loading. Faint cracks appeared in the region of the wheel path at about 75,000 load applications and propagated as there was more loading. During the drainage tests, some water was forced up to the surface through these cracks. Most of the rutting occurred in the subgrade, apparently because of consolidation and piping of the fines.

Section 2 was removed after 118,900 load applications. When the section was opened up, the OGBAM matrix in the region of the wheel path had loosened and could be removed with only a shovel. Also, the OGBAM particles had become coated with dirt.

Table 10. Coefficient of permeability of layers of open-graded bituminous aggregate mixtures.

Load Applications	Coefficient of Permeability by Section (ft/day × 1000)					
	1	2	3	4	5	6
224	37.9	46.2	39.5	33.2	20.9	36.3
8,200	26.8	35.7	23.9	22.3	14.5	25.0
20,000	24.8	32.2	27.0	20.5	16.0	24.1
50,000	20.6	22.6	15.1	18.1	13.1	21.9
101,000[a]	16.7	19.0	14.4	15.1	12.0	17.9
118,900	16.7	8.3[b]	13.0	12.3	12.5	20.6
148,000[a]	15.4	—	11.1	13.9[bc]	12.6	18.1
246,074	10.1	—	5.1	—	12.3	18.0

Note: 1 ft = 0.3048 m.

[a]Application of loads during drainage test.
[b]Test conducted before removal of test section.
[c]Water passed through section 4 without load application.

Figure 4. Coefficient of permeability versus load applications.

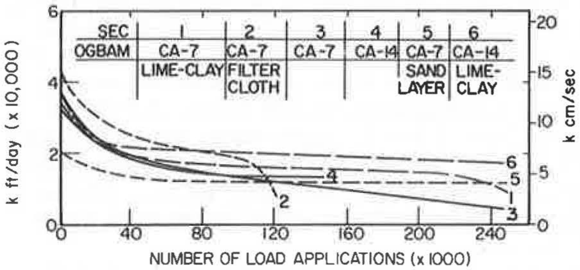


Figure 5. Turbidity of discharge water at 100.000 load applications.

The state of the filter cloth could not be determined because it had been damaged during removal of the OGBAM layer. However, it appeared to have withstood, without damage, the high temperature [about 300 F (150 C)] to which it was subjected during placement of the OGBAM.

Section 3

Section 3 was made of an asphalt concrete surface course and an OGBAM (CA-7) drainage layer placed directly over the subgrade.

The drainage trend of the drainage layer is shown in Figure 4. The coefficient of permeability of the drainage layer decreased by almost half from an initial value of 39,500 ft/day (13.9 cm/s) to 21,000 ft/day (7.4 cm/s) at 50,000 load applications. It continued to decrease at an almost constant rate with further load applications to 5,100 ft/day (1.8 cm/s) at the end of the testing program. Slightly turbid water was discharged when loading was initiated simultaneously with the drainage test. The discharged water became quite turbid during further load applications, and, by 138,000 applications, very dirty water was discharged (Table 9). The level of turbidity of the discharge water at 100,000 load applications can be seen in Figure 5.

Little rutting took place in this section, and the maximum rut depth was about ¼ in. (6 mm) at the end of testing.

When the section was opened up at the end of the testing program, the OGBAM matrix in the region of the wheel path was loose and was covered substantially with dirt to the extent that the OGBAM looked as if it were almost clogged with fines. The OGBAM between the wheel path and the outlet end was also covered with fines from a depth of about 3 in. (7.6 cm) near the wheel path to about 2 in. (5.0 cm) near the outlet end.

Section 4

Section 4 was made of an asphalt concrete surface course and an OGBAM (CA-14) drainage layer placed directly over the subgrade.

The drainage trend of the drainage layer is shown in Figure 4. The coefficient of permeability of the drainage layer decreased by almost half from an initial value of 33,200 ft/day (11.7 cm/s) to 18,100 ft/day (6.4 cm/s) at 50,000 load applications and decreased gradually with further load applications to a value of 13,900 ft/day (4.9 cm/s) at 145,940 load applications when the section was removed from test because of excessive rutting. As can be seen in Table 9, some fines washed out with the discharged water when the first loading was applied simultaneously with water for the drainage test. As there were further load applications, the quantity of fines washing out increased, and at the time of removal of the section the turbidity of the discharge water had reached a level of slightly dirty water. Figure 5 shows the turbidity levels at 100,000 load applications.

Rutting progressed rapidly in this section, and the rut depth at the point of maximum rutting progressed from 1³⁄₁₆ in. (30 mm) at 90,000 load applications to 2 in. (50 mm) at 145,940 load applications. A faint crack appeared in the middle of the section at about 140,000 load applications, and some water was forced to surface during subsequent drainage tests. Transient deflections were observable after about 144,000 load applications. Most of the rutting in this section occurred in the subgrade.

The section was removed after 145,940 load applications. When the section was opened up, the OGBAM was loose in the region of the wheel path and could be shoveled out. The OGBAM particles were covered with dirt.

Section 5

Section 5 was made of an asphalt concrete surface course, an OGBAM (CA-7) drainage layer, and a sand filter (torpedo sand) placed over the subgrade.

The drainage trend of the drainage layer is shown in Figure 4. The coefficient of permeability of the drainage layer decreased by about a third from an initial value of 20,900 ft/day (7.4 cm/s) to 13,000 ft/day (4.6 cm/s) at 50,000 load applications. There was no significant decrease in the rate of discharge with further load applications, i.e., the coefficient of permeability stabilized at about 12,700 ft/day (4.5 cm/s). Because the lip of the catch basin was formed over the sand filter layer, the turbidity data may not be relevant; however, clear water was discharged throughout the testing program.

Rutting progressed gradually as there was more loading from $\frac{3}{4}$ in. (19 mm) at 90,000 load applications to $1\frac{1}{2}$ in. (3.8 cm) at the point of maximum rutting at 246,074 load applications. Rutting occurred primarily in the sand layer and was apparently due to consolidation.

When the section was opened up at the end of the test, the OGBAM matrix was loose in the region of the wheel path. Sand had filtered from about $\frac{1}{2}$ in. (13 mm) to $\frac{3}{4}$ in. (19 mm) into the OGBAM layer.

Section 6

Section 6 was made of an asphalt concrete surface course, an OGBAM (CA-14) drainage layer, and a 2.6-in. (6.6-cm) lime-clay mixture layer placed over the subgrade.

The drainage trend of the drainage layer is shown in Figure 4. The coefficient of permeability of the drainage layer decreased by about 40 percent from an initial value of 36,300 ft/day (12.8 cm/s) to 21,900 ft/day (7.7 cm/s) at 50,000 load applications and decreased gradually with further load applications to 18,000 ft/day (6.4 cm/s) at 246,074 load applications. As can be seen from Table 9, clear water was discharged until almost the end of the test. Some fines washed out with the discharge water after about 230,000 load applications. The clearness of the discharge water at 100,000 load applications can be seen in Figure 5.

Rutting progressed gradually to a maximum rut depth of $1\frac{1}{16}$ in. (27 mm) at the end of the testing program (246,074 load applications). The surface layer consolidated, and some rutting occurred in the lime-clay mixture layer.

When the section was opened at the end of the test, the OGBAM matrix was loose within the region of the wheel path; however, the dirt covering the particles was confined only to the lower region of the drainage layer, and the upper region seemed relatively free of the dirt cover. About $\frac{1}{2}$ in. (13 mm) of the drainage layer had penetrated into the lime-clay mixture.

DISCUSSION OF RESULTS

From previous experience on the test track, we feel that the test track loading on the OGBAM layer is significantly more severe than the expected loading on an OGBAM layer used as a subbase for concrete pavements. Similarly, the stresses in the OGBAM layer and the subgrade of the typical test section, which were caused by a 3,200-lb (145-kg) wheel load, were significantly higher than the stress levels expected in the OGBAM layer and the subgrade when they were used as a subbase for a concrete slab on which typical highway loading had been applied. Other factors also contributed to the severity of loading. The loads in the test track are applied at a greater frequency; therefore, the recovery time between loads is decreased. The twisting action of the tire on pavement as the loading frame revolves around the track probably adds an additional component of stress to the pavement. Thus, the structural and drainage distress levels (washing out of fines) were relatively higher in the test sections than were expected under a typical concrete slab pavement.

As can be observed from the test results, all the drainage layers started out with a high coefficient of permeability that decreased substantially during initial loading. Figure 4 shows the trend of the change in coefficient of permeability with respect to loading for all sections. The initial changes in the coefficients of permeability are similar in all the sections except for section 5, which started out with a lower coefficient value. It appears likely that these changes were due to initial consolidation and rearrangement of the particle matrix in the OGBAM layers. This phenomenon should be greatly reduced in a typical pavement installation because of much lower anticipated stress levels and lower levels of deflection.

The experimental design was formulated to allow the comparison and the evaluation of the effects of different variables with various replications. By comparing the responses of sections 1 and 6 and sections 3 and 4, one can see that the effect of aggregate gradation, the CA-7 type of gradation as compared to the CA-14 type of gradation, seems not to be significant in regard to permeability. However, as can be seen from Table 9, sections 1 and 3, which had OGBAM layers with CA-7 aggregate gradation (slightly coarser gradation than that of the CA-14 aggregates), exhibited a more pronounced tendency for washing out the subgrade fines. Consequently, they also had a greater tendency to plug than did their corresponding sections 6 and 4.

The effect of the different design variables can be evaluated by comparing the response of the 4 sections that had OGBAM layers made of CA-7.

Section 2, which had the OGBAM layer on a filter cloth, gave the poorest performance. It appears that the repeated dynamic loadings caused the subgrade fines to filter through the openings of the filter cloth (average size opening equal to that of a No. 140 mesh sieve). The fines subsequently washed out. Section 3 gave a poor performance in terms of drainage, but for some reason little rutting occurred. Sections 1 and 5 showed stable behavior in terms of drainage capacity. After the initial decrease in the permeability, a gradual decrease took place as more loads were applied.

Because of the open-graded nature of the OGBAM, sufficiently accurate measurement could not be made of the degree of compaction achieved during construction of the OGBAM layers. Therefore, the correlation between the amount of voids in the OGBAM and the drainage characteristics cannot be made with any confidence. The measured bulk specific gravity of the OGBAM layers ranged from 1.74 to 1.82. The average voids content in the OGBAM was 29.1 percent, and the time required to fill up these voids after inflow was initiated was 10 min. However, in most sections, water appeared at the outlet end after about 2 min 30 s, and the steady state of the flow was attained within 1 additional min. Therefore, it is possible that for most of the length of flow only a part of the cross-sectional area of the OGBAM layer was used for the flow of water. If this is true, higher values for the coefficients of permeability than indicated earlier would result. Consequently, the coefficient of permeability values presented in this paper should be considered conservative.

The modification of the characteristic of subgrade clay soil with small quantities of lime (2 percent) can be highly beneficial in lime-reactive soils. The cohesive nature of the lime-modified clay restricted the washing out of the subgrade fines; however, the behavior of lime-modified clay when the pavement is subjected to a high degree of groundwater seepage or significant frost action will need further investigation.

At the end of the testing of each section, it was observed that the OGBAM matrix within the region of the wheel path had become unbound and could be shoveled out of most sections. This may have been due to an inadequate asphalt cement film covering the aggregate particles, which resulted in the fatigue of the asphalt cement bond between the particles, which was caused by the heavy repeated wheel loads. In a rigid pavement, the looseness of the OGBAM may pose few problems, but in a flexible pavement this loss of bond may cause a loss in pavement performance. For in-service pavements, this problem can possibly be reduced by imposing a maximum allowable stress on the OGBAM layer and restricting the total resilient deformation. It is probable that the use of softer and slightly increased amounts of asphalts could be effective in securing a more lasting bond between the aggregate particles.

This study was designed to evaluate the performance of drainage sections by the consideration of only surface water inflow, and this fact should be remembered when the results of this study are used.

CONCLUSIONS

In terms of the objectives of the study, the following conclusions can be drawn from the results. OGBAM layers possess a high order of permeability. No significant difference was observed in the drainage behavior of OGBAM with CA-7 aggregates and that with CA-14 aggregates. For design purposes, the coefficient of permeability values for either gradation of OGBAM can be conservatively estimated at 10,000 ft/day (3.5 cm/s). The use of OGBAMs in a properly designed pavement structure is not detrimental to the overall performance of the system. The limited results show that

1. Satisfactory performance can be obtained by incorporating a sand filter with the OGBAM drainage layer.
2. OGBAM drainage layers placed on modified clay subgrades can be expected to perform at a higher level than those placed directly on natural clay subgrades.
3. Use of a filter cloth in a structural drainage section subjected to heavy wheel loads and high inflows of water into the pavement section may be detrimental to the performance of the pavement system.

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