Determination of Free-Draining Base Materials Properties

HAIPING ZHOU, LUCINDA MOORE, JIM HUDDLESTON, AND JEFFREY GOWER

Recently, Oregon designed and constructed two types of permeable bases under both flexible and rigid pavements: an asphalt-treated permeable material (ATPM) and an open-graded aggregate material. Permeability and resilient modulus of both materials have not been determined. During pavement structural design using the *AASHTO Guide for Design of Pavement Structures*, 1986, layer and drainage coefficients had to be assumed to establish pavement thickness designs. In addition, construction with the existing open-graded aggregate revealed that the material was less stable and would ravel easily under construction traffic. In 1990, a research project was initiated to determine the desirable material properties for the two types of free-draining base materials and establish a more stable gradation for the open-graded aggregate base. This project consisted primarily of a laboratory investigation. Pavement cores of the asphalt-treated permeable base and samples of aggregate materials were tested in the laboratory for permeability and resilient modulus. The permeability was determined using both constant and falling head test procedures. The laboratory study indicated that the current Oregon ATPM has a sufficient drainage capability, and the resilient modulus of this material is typical of the findings of other states. A modified open-graded aggregate gradation resulted, which has a higher permeability and higher resilient modulus than the existing gradation. Recommendations for implementation include selection of layer and drainage coefficients for pavement structural design and use of the proposed open-graded aggregate gradation in pavement construction.

Inadequate drainage of pavement structures has been identified as one of the primary causes of pavement distress (*1–3*). For many years, researchers have theorized that improving pavement drainage might combat many pavement problems and extend the pavement service life (*4*). Subsurface drainage includes the disposal of water that has entered the pavement structure; therefore, a positive drainage layer in a pavement structure is critical for subsurface drainage. The subsurface drainage system can be designed by providing a drainage layer along with transverse and longitudinal drainage pipes to remove the water from the pavement structure.

Recently, Oregon initiated the design and construction of permeable bases under both flexible and rigid pavements. Two types of permeable bases used are an asphalt-treated permeable material (ATPM) and an open-graded aggregate material with the existing gradation designed by Oregon. Permeability and resilient modulus of both materials have not been determined. During pavement structural design, using the *AASHTO Guide for Design of Pavement Structures* (*5*), layer and drainage coefficients had to be assumed to establish pavement thickness designs. In addition, construction with the existing open-graded aggregate gradation revealed that the material was less stable and would ravel easily under construction traffic. Because of this ravelling, compaction was poor, the grade was difficult to control, and the open-graded aggregate materials did not provide a suitable surface for paving.

In 1990, a research project was initiated to better understand the characteristics of these two types of permeable base materials, develop appropriate layer and drainage coefficients for use in pavement thickness design, and improve stability and constructability of the existing open-graded aggregate material.

This project included (a) obtaining pavement cores of the ATPM and several gradations of aggregate base materials for testing permeability and resilient modulus in the laboratory (for aggregate materials, the effect of fractured faces was also examined, (b) recommending appropriate layer and drainage coefficients for use in pavement thickness design on the basis of laboratory test results, and (c) establishing an optimum gradation to improve stability and constructability of the open-graded aggregate material. For comparison, material properties of a dense-graded aggregate material were also investigated.

LITERATURE REVIEW

A literature review revealed that permeable bases can generally be grouped into two categories: (a) treated permeable base, in which aggregate material is typically mixed with 2 to 4 percent asphalt or a certain percentage of portland cement, (the asphalt treatment is more commonly used) and (b) open-graded aggregate material that is used directly in pavement base construction.

Use of Treated Permeable Base

The treated permeable base, especially the asphalt-treated permeable material (ATPM) base, has been widely used in the United States. In 1990 the National Asphalt Pavement Association distributed a questionnaire to the 50 state transportation departments. Of the 30 states indicating use or planned use of ATPM, 25 place the ATPM directly below the surfacing for interception of infiltrated surface runoff and 11 place the ATPM above the subgrade (*6*).

H. Zhou, Nichols Consulting Engineers, Chtd., 1885 South Arlington Avenue, Suite 111, Reno, Nev. 89509. L. Moore, J. Huddleston, and J. Gower, Oregon Department of Transportation, 800 Airport Road, S.E., Salem, Oreg. 97310.

The thickness required for drainage can be calculated using Darcy's law (*7–9*). Mathis (*9*) indicates that 4 in. of ATPM would provide sufficient capacity, be easily constructed, and provide for construction variability. Forsyth (*6*) indicated that the ATPM thickness ranged from 2 to 6 in., with 4 in. the most common.

The coefficient of permeability (k) of the ATPM can be affected by a number of factors, such as aggregate gradation and asphalt content used in the mixture. Although permeability of the ATPM would not be reduced significantly with the addition of 2 to 3 percent asphalt cement (*10*), it can vary from 3,000 to 15,000 ft/day (*9*), depending on the aggregate gradation.

Hicks et al. (*11*) reported ATPM resilient modulus averaging 155,000 to 270,000 psi at 75°F, depending on confining pressure. Monismith et al. (*12*) reported an average resilient modulus of 159,000 psi on samples consisting of partially crushed gravel.

Layer coefficients are used in the AASHTO guide (*5*). The value of layer coefficients used in design varied among the states that used ATPM. Forsyth (*6*) reported that of the 30 states that have or plan to use ATPM, 11 give it no structural value, 10 assign a layer coefficient corresponding to aggregate base between 0.10 and 0.14, and 6 assign layer coefficients between 0.20 and 0.30. California Department of Transportation (Caltrans) conducted a research project in 1981 with the objective of establishing a gravel factor for ATPM based on deflection attenuation resulting from the placement of a 3-in. ATPM layer. The results suggested a gravel factor corresponding to an AASHTO layer coefficient of approximately 0.20. If a resilient modulus of 140,000 psi is assumed for the ATPM, the procedure suggested by Rada et al. (*13*) results in an AASHTO layer coefficient of 0.23 (*6*).

Use of Untreated Permeable Base

Untreated permeable bases have also been used in a number of states. To provide sufficient drainage capability, the untreated permeable base is typically constructed with open-graded aggregate materials. In Oregon, this is often referred to as free draining aggregate material (FDAM).

The FDAM layer thickness required for drainage can be determined using Darcy's law (*7,8,14*). There is not much information indicating typical thickness used by other states. Oregon has been using 6 to 15 in. of FDAM in pavement construction. A minimum 6-in. FDAM appears to be necessary to have a proper compaction and minimum drainage requirement, although layer thicknesses greater than 12 in. may be difficult to compact. In 1991, the Oregon State Highway Division (OSHD) conducted a survey of OSHD project managers concerning the use of the FDAM with the current gradation (Table 1). One question was specifically related to the compaction of the FDAM. The respondents to the question indicated that the FDAM was unstable and that good compaction was difficult to achieve. Therefore, modifications to the current FDAM gradation should be made to produce a more workable and stable base material.

Gradation is the primary factor affecting the permeability of the FDAM. Mathis (*9*) indicated that the untreated permeable base materials generally had a lower coefficient of permeability than the treated permeable base materials. The estimated permeability for the untreated base materials is in the range of 200 to 3,000 ft/day.

TABLE 1 Current Aggregate Gradation for Oregon's FDAM

Sieve Passing	Percent by Weight
1-1/2"	100
1"	95-100
3/4"	55-80
1/4"	25-50
No. 10	0-15
No. 100	0-3 (Dry Sieve)

Oregon's FDAM resilient modulus has not yet been determined. However, a slightly lower modulus than typical dense-graded aggregate is expected because of the large air voids. Many studies (*15–21*) show that the resilient modulus of untreated aggregate materials is a function of material types and stress state occurring in the material. This is also to be expected for the FDAM.

Mathis (*9*) reported that test results from New Jersey and Pennsylvania indicated the untreated permeable material had similar bearing capacities to dense-graded aggregate bases. This may imply that the same layer coefficient can be assigned for both a permeable and dense-graded aggregate base in pavement design.

LABORATORY STUDY

To accomplish the research objectives, a laboratory study was conducted. The study included permeability and resilient modulus tests on both the ATPM and the FDAM used in Oregon. For permeability tests, both constant and falling head testing procedures were used. The effect of untreated aggregate fractured faces on permeability and resilient modulus was also investigated.

Permeability Tests

The purpose of the tests was to determine the coefficient of permeability (k) for the materials to be used. The apparatuses for the permeability tests were developed by the Pavements Unit of OSHD.

The constant head permeability test procedure determines the permeability of a material by maintaining a constant head (h) on the sample surface and measuring the time needed for collecting a known amount of water. The permeability can then be calculated using the equation

$$k_c = \frac{QL}{Ah} * 7200 \qquad (1)$$

where

k_c = coefficient of permeability (ft/day), from constant head test;
Q = flow quantity (in.^{3}/sec);

L = flow path length or sample height (in.);
A = flow path area or sample area (in.^{2}); and
h = constant water head (in.).

The falling head permeability test determines the permeability of a material by measuring the time required for the water head to drop from a high level (h_1) to a low level (h_2). The permeability is then calculated using the equation

$$k_f = \frac{L}{T} \ln \frac{h_1}{h_2} * 7200 \qquad (2)$$

where

k_f = coefficient of permeability (ft/day), from falling head test;
L = flow path length or sample height (in.);
T = time required for water head dropping from h_1 to h_2 (sec); and
h_1, h_2 = water levels (in.).

Resilient Modulus Tests

The resilient modulus is a measure of the stiffness and a dynamic test response defined as the ratio of the repeated axial deviator stress to the recoverable axial strain. For this study, resilient modulus tests were performed to develope layer coefficients of the asphalt-treated permeable base and untreated aggregate base materials and to determine a relative stability for the untreated materials.

ATPM Test Results

Sample Preparation

Asphalt-treated base core samples were obtained from two projects, both constructed in 1990. The Fir Grove Lane–Towers Road project (*22*) has a 4-in. ATPM, and the Rose Lodge–Polk County Line project (*23*) has a 3-in. ATPM. Core samples obtained from the project sites were cut and trimmed in the laboratory for permeability and resilient modulus testing. The prepared core samples were typically 1.8 to 2.5 in. thick. The diameter of the core samples was 4 in. One additional 6-in. core was also taken from each project. The 6-in. core was used in extraction tests to determine actual asphalt content and aggregate gradation. For the Fir Grove Lane–Towers Road project, 2.9 percent of PBA-2 (Performance Based Asphalt) was used. For the Rose Lodge–Polk County Line project, 2.4 percent of AC-15 asphalt was used. The aggregate gradations are in general within the specification limits, as given in Table 2.

Permeability

Permeability tests were performed following the procedures previously described. The test results (Table 3) show that for each test procedure the permeability varied substantially. For instance, the permeability for the Fir Grove Lane–Towers Road project ranges from 494 to 3,568 ft/day with the constant head test procedure and from 1,032 to 4,130 ft/day with the falling head test procedure. The variation in permeability on the same project may be due to the nonuniformity of the core material, although the variation of the permeability from two testing procedures may be due to the difference in the way water is introduced to the sample during the testing. It was difficult to maintain a constant water flow using the constant head testing procedure.

TABLE 2 Extraction Test Results

Aggregate Sieve Size	Percent Passing		Specification Limit
	Fir Grove Road	Rose Lodge Road	
1"	100	100	99 - 100
3/4"	94	(98)	85 - 95
1/2"	(68.6)	66	35 - 68
1/4"	19	19	5 - 20
#10	(6.1)	5	0 - 5
#40	4.1	3	-
#200	(2.7)	1.9	0 - 2
Asphalt Content	2.9	2.4	2 - 3

Note: Values in parenthesis exceeded specification range.

Resilient Modulus

The resilient modulus test on ATPM was conducted in accordance with ASTM D4123 standard procedure (*24*). Table 4 gives a summary of the test results. The resilient moduli from both projects are generally similar, with an average of approximately 100 ksi. The resilient modulus tests were performed at room temperature, approximately 77°F.

Bulk specific gravity test results are also given in Table 4. The average bulk specific gravity of the Fir Grove Lane–Towers Road project is about 10 percent lower than that of the Rose Lodge–Polk County Line project. The estimated air voids for the ATPM material are in the range of 20 to 25 percent.

FDAM Test Results

Gradations

Aggregate materials from a local source were obtained. Six different gradations were used to determine their permeability and resilient modulus. These gradations are existing open-graded aggregate, existing dense-graded aggregate, New Jersey open-graded aggregate, and proposed open-graded aggregate at the low end, center, and high end of the broadband limit. Table 5 gives the gradation for each aggregate. For the proposed open-graded aggregate, the samples prepared with 88 percent fractured faces aggregate were fabricated at both upper- and lower-bound specification limits, and the samples prepared with 100 percent fractured faces aggregate were fabricated at the center of the specification limit. The gradation difference is given in Figure 1. The proposed open-graded aggregate gradation is very similar to that of New Jersey (*25*).

TABLE 3 Permeability Test Results on ATPM Cores

Project Name	Sample I.D.	Permeability (ft/day)	
		Constant Head	Falling Head
Fir Grove Lane - Towers Road	1	1520	1959
	2	1618	1926
	3	2640	1920
	4	494	1032
	5	970	1299
	6	719	1086
	7	1693	2671
	8	1200	2517
	9	3568	4130
	10	628	1513
	Average	1505	2005
	Standard Deviation	965	929
	Range	494 - 3568	1032 - 4130
Rose Lodge - Polk County Line	1	Broken	
	2	3379	2273
	3	2506	1849
	4	3147	2273
	5	1518	1761
	6	1960	1678
	7	2360	2012
	8	2499	2326
	9	2348	2153
	10	Broken	
	Average	2465	2041
	Standard Deviation	595	253
	Range	1518 - 3379	1678 - 2326

TABLE 4 Summary of ATPM Resilient Modulus Test Results

Sample I.D.	Resilient Modulus (ksi)[1]	Bulk Specific Gravity
Project: Fir Grove Lane - Towers Road		
1	99	2.29
3	137	2.26
4	176	2.22
6	38	2.24
8	153	2.27
10	119	2.25
Average	120	2.26
Standard Deviation	48	0.02
Project: Rose Lodge - Polk County Line		
2	103	2.51
4	64	2.54
5	90	2.53
6	76	2.51
7	94	2.55
9	74	2.57
Average	84	2.54
Standard Deviation	15	0.02

[1] Measured at room temperature, about 77°F.

TABLE 5 FDAM Gradation

Aggregate with 88% fractured faces					
Aggregate Sieve Size	Existing open Graded[1] (A)	New Jersey[1] (B)	Proposed Upper Bound (C)	Proposed Lower Bound (D)	Existing Dense Graded[1] (H)
1-1/2"	100	100	100	100	97.5
1"	97.5	97.5	100	100	80
3/4"	67.5	86	98	80	64
1/2"	56.5	70	85	60	54
1/4"	37.5	54	60	45	42
#10	7.5	12.5	20	5	23
#40	4	3	6	0	12
#200	1	1.5	5	0	5

Aggregate with 100% fractured faces			
Aggregate Sieve Size	New Jersey[1] (E)	Proposed Open Graded[1] (F)	Existing Dense Graded[1] (G)
1-1/2"	100	100	97.5
1"	97.5	100	80
3/4"	86	89	64
1/2"	70	68	54
1/4"	54	53	42
#10	12.5	13	23
#40	3	3	12
#200	1.5	2.5	5

Note: All values are percent passing by weight
[1] Center value of the specification limit.

To evaluate the effect of fractured faces of aggregates on permeability and resilient modulus, aggregates with 88 and 100 percent fractured faces were tested. The percentage of fractured faces was determined following the OSHD TM-213 test procedure (*26*). The OSHD TM-213 is a visual inspection procedure for determining the percent, by weight, of the rock retained on the ¼-in. sieve having at least two fractured faces. For comparison, both open- and dense-graded aggregates were evaluated.

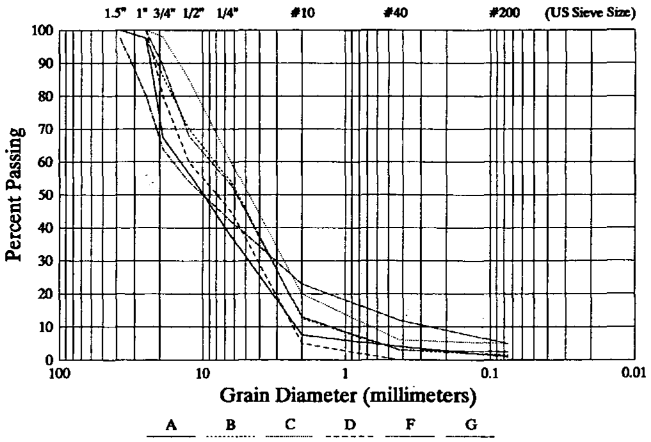

FIGURE 1 Aggregate gradations.

Sample Preparation

Ten samples at each gradation were made. Five were tested for permeability and five for resilient modulus. Eighty samples were prepared for the laboratory study. All samples were to be made on the basis of their water-density relationships, which were determined before sample preparation. The maximum dry density and the optimum moisture content for each gradation is shown in Table 6.

Samples for the permeability test were 4 in. in diameter and 6 in. high. For the resilient modulus test, samples were 6 in. in diameter and 12 in. high. All samples were to be prepared at the optimum moisture contents.

Permeability

The permeability test results (Table 7 and Figure 2) indicate that for open-graded aggregates, the percent of fractured faces have a substantial influence on the permeability. For the same gradation, as shown by Gradations E and B, the aggregate with 100 percent fractured faces is more permeable than aggregate with 88 percent fractured faces. The bound limit also influences the permeability significantly. As can be seen for the proposed aggregate gradation, the lower-bound Gradation D has a much higher permeability than the upper-bound Gradation C. This is to be expected because Gradation D is much coarser than Gradation C. Gradation F is the centerline of the proposed gradation band. With 100 percent fractured

TABLE 6 Maximum Dry Density for Each Gradation

Gradation	Maximum Dry Density (pcf)	Optimum Water Content (%)
A	115.5	6.5
B	112.2	4.0
C	108.6	8.0
D	105.0	6.0
H	120.3	5.3
E	117.6	3.5
F	115.9	3.2
G	123.6	3.3

TABLE 7 Summary of Permeability Test Results for Untreated Base Materials

Sample I.D.	Constant Head (ft/day)		Falling Head (ft/day)	
	Average	Standard Deviation	Average	Standard Deviation
A	971	322	1031	223
B	770	138	723	145
C	226	42	316	77
D	3018	370	3694	143
H	140	64	76	30
E	2376	338	1962	181
F	2489	309	1876	169
G	475	150	153	31

faces, Gradation F is expected to have a higher permeability than with 88 percent fractured faces, as shown by Gradations E and B. The results also show that the permeability of Gradation F is closer to that of Gradation D, which is the lower bound of the proposed gradation limit. This appears to indicate that as the percentage of aggregate fractured faces increases, the permeability of the aggregate material would also increase. For dense-graded aggregate, the difference in permeability due to fractured faces is not substantial.

The permeability test results from both constant and falling head test procedures appear in general to be similar for each type of aggregate gradation. The permeability results from the falling head test appear to have a smaller standard deviation than those from the constant head test.

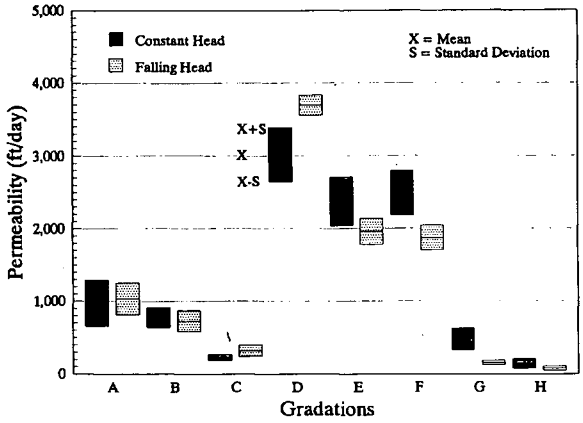

FIGURE 2 Comparison of permeability from different gradations.

Resilient Modulus

The resilient modulus test on untreated aggregate base materials was conducted in general accordance with AASHTO T-274 procedure (*27*), which was the standard testing method available for unbound materials. The test results are given in Table 8. The resilient modulus results are

$$M_R = k_1\,\theta^{k2} \tag{3}$$

where

M_R = resilient modulus (psi),
k_1, k_2 = regression coefficients of material, and
θ = bulk stresses (psi).

This expression shows that the resilient modulus of untreated aggregate is a function of both bulk stress and material properties.

The resilient modulus test results indicate that for open-graded aggregates the percent of fractured faces has a significant influence on the resilient modulus. For the same type of gradation, the aggregates with 100 percent fractured faces have a much higher resilient modulus than aggregates with 88 percent fractured faces, as shown in Figure 3 (*top*). For dense-graded aggregate, the difference in resilient modulus due to fractured faces is not obvious, as shown in Figure 3 (*bottom*).

Figure 4 (*top*) shows the test results for the proposed aggregate gradation versus the existing aggregate gradation. The figure clearly shows that the proposed FDAM Gradation F had a higher resilient modulus than the existing FDAM Gra-

TABLE 8 Summary of Resilient Modulus Test Results for Untreated Aggregate Materials

Gradation	Modulus = $k_1\theta^{k_2}$	R^2	Actual Dry Density (pcf)[a]	Actual Water Content (%)[a]
A	$2{,}557\theta^{0.592}$	0.92	107.6	3.4
B	$1{,}943\theta^{0.619}$	0.96	104.1	3.9
C	$1{,}786\theta^{0.615}$	0.87	102.6	5.8
D	$3{,}240\theta^{0.568}$	0.94	105.4	3.4
H	$4{,}144\theta^{0.525}$	0.95	120.2	4.5
E	$4{,}054\theta^{0.574}$	0.74	119.1	2.9
F	$3{,}475\theta^{0.569}$	0.81	116.3	2.6
G	$4{,}355\theta^{0.511}$	0.94	124.1	2.9

[a] Average of test results from five samples for each gradation.

dation A. For comparison, resilient moduli for each gradation are plotted in Figure 4 (*bottom*).

Table 8 also gives actual dry density and water content data measured immediately after the resilient modulus test. Some of the actual dry densities measured during resilient modulus test are slightly higher than the maximum dry densities determined during the development of water-density relationship for the aggregate materials, and the actual moisture content of the samples is slightly lower than optimum water content. The exact cause of inconsistency in dry densities is not known. It may have been caused by variation in sample fabrication, which was conducted by two different laboratories. The slightly lower actual water content of the samples may have been caused by water loss during the modulus testing process.

USE OF RESEARCH RESULTS

The laboratory test results have been analyzed for the development of design inputs and specification for use in Oregon. The design inputs include resilient modulus and layer coefficients. The specification includes recommendation for modification of the current FDAM gradation of OSHD.

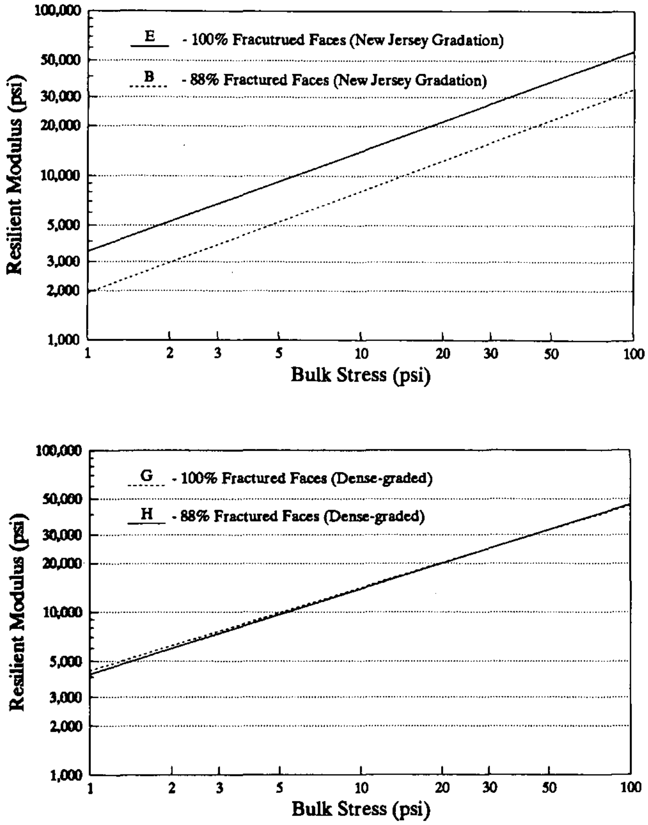

FIGURE 3 Effect of fractured faces on resilient modulus: *top*, open-graded aggregate; *bottom*, dense-graded aggregate.

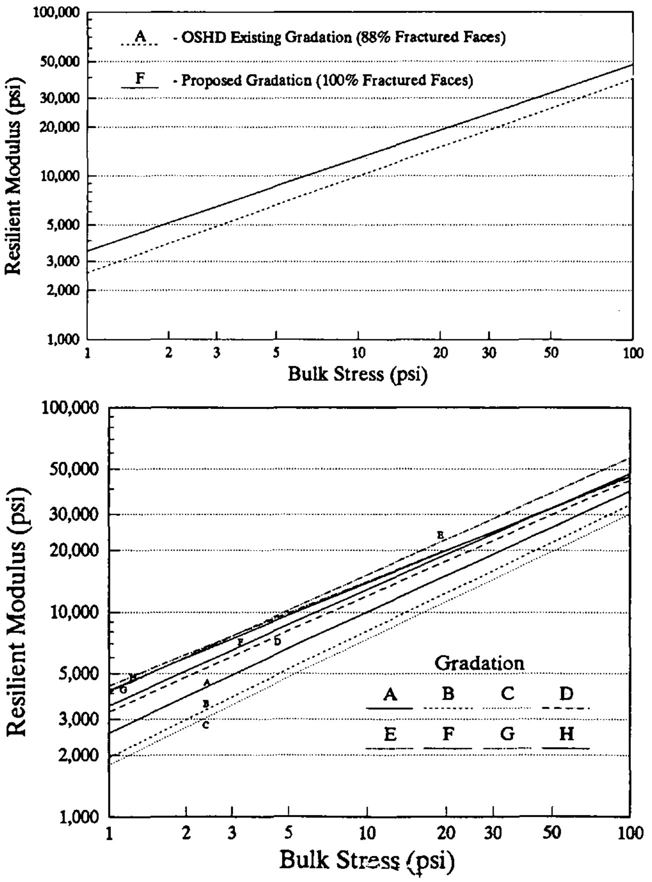

FIGURE 4 Comparison of resilient moduli: *top*, proposed gradation versus existing gradation; *bottom*, all aggregate gradations investigated.

ATPM Resilient Modulus and Layer Coefficient

For the Fir Grove Lane–Towers Road project, the average resilient modulus measured in the laboratory is 102 ksi with a standard deviation of 48 ksi. For the Rose Lodge–Polk County Line project, the average resilient modulus is 84 ksi with a standard deviation of 15 ksi. The resilient modulus of the ATPM was measured at 77°F without confinement, and the stiffness of ATPM would vary with the change of temperature. Although a modulus-temperature relationship for Oregon's ATPM is not known, it is expected that the modulus will increase when temperature decreases. In Oregon the ATPM base layer may experience a much lower temperature than 77°F because of its position in the pavement structure. Therefore, the actual modulus may be much higher than those measured in the laboratory.

Considering the temperature effect on the resilient modulus and using a modulus-layer coefficient conversion chart recommended by AASHTO (*5*), a corresponding layer coefficient can be determined. For Oregon's ATPM, the average resilient moduli are adjusted to 68°F using a procedure in the AASHTO guide (*5*). The temperature-adjusted resilient moduli are then used to determine the layer coefficient. This would result in a layer coefficient between 0.14 and 0.19.

The drainage coefficient should be included in the pavement structural design. For pavements to provide a positive drainage, a minimum permeability of 1,000 ft/day should be achieved (*2,28*). Oregon's current ATPM appears to have a sufficient drainage capability, as can be seen from the laboratory test results in Table 3. With this drainage capability, a drainage coefficient between 1.15 to 1.25 is recommended for use in Oregon. This recommendation is based on an assumption that the pavements would have a good quality of drainage and 1 to 5 percent of the time during the year the pavement structure would be exposed to moisture levels approaching saturation (*5*).

FDAM Resilient Modulus and Layer Coefficient

The layer coefficient for the FDAM may be determined knowing the resilient modulus, which can be calculated from Equation 3. For a specific aggregate material, a corresponding equation or relationship should be used to calculate the modulus. The resilient modulus for untreated aggregate is a function of stress state in a pavement structure; therefore, an anticipated stress level should be used to determine the resilient modulus. Guidelines for determining stress state may be found in the AASHTO guide (*5*). For pavement design in Oregon, a layer coefficient between 0.08 to 0.14 is recommended for both base and subbase layers. These correspond to a resilient modulus between 16 to 30 ksi for the base and 11 to 20 ksi for the subbase materials.

A drainage coefficient between 1.00 to 1.15 is recommended for use in Oregon. This recommendation is based on an assumption that the pavements would have a good quality of drainage, and 5 to 25 percent of the time during the year pavement structure would be exposed to moisture levels approaching saturation. The percent of time FDAM moisture levels approach saturation is higher than that of the ATPM; this is because of concerns about contamination of the FDAM. Also, most FDAM designs have not provided longitudinal edge drains. Consequently, water is outlet on the shoulder; therefore, the shoulders may become contaminated over time. If edge drains are provided, a higher drainage coefficient may be appropriate.

Gradation Specification Changes

One objective of this paper is to evaluate the existing FDAM gradation and its performance during construction. The OSHD project manager questionnaire survey indicated that the existing gradation was unstable and difficult to compact during construction. An appropriate modification of this gradation has been made in using as much of the existing aggregate stockpile as possible. This modification (newly proposed) is represented by Gradation F with 100 percent fractured faces. The broadband of the proposed gradation is shown in Table 9.

Laboratory tests on Gradation F showed a substantial increase in resilient modulus as well as in density, compared with the existing gradation. This improvement in material property, due to gradation changes and increased fractured faces percentage, may also improve its constructability and stability. Another major improvement due to gradation change is a considerable increase in permeability. Compared with the

TABLE 9 Proposed Gradation Specification

Sieve Size	Percent Passing % (Centerline)	Broadband Limit
1-1/2"	100	100
1"	100	100
3/4"	89	80-98
1/2"	68	60-85
1/4"	53	45-60
#10	13	5-20
#40	3	0-6
#200	2.5	0-5
Measured permeability (ft/day)	Constant Head	Falling Head
Average Standard deviation	2,489 309	1,876 169

existing gradation, the permeability of the modified gradation is almost double.

CONCLUSIONS

1. Many states are paying great attention to subsurface drainage. The design and construction of a positive drainage system in pavement structures is becoming more common.
2. Typical ATPM layer thickness ranges from 3 to 4 in. The typical asphalt content used in ATPM is 2 to 3 percent. Within this range, the amount of asphalt appears to have a minor influence on permeability.
3. The current ATPM of OSHD has sufficient drainage capability. The resilient modulus of this material is typical of the findings of other states.
4. The proposed gradation for open-graded aggregate with 100 percent fractured faces has a considerably higher permeability than the existing gradation. The aggregate with the proposed gradation also has a higher resilient modulus.
5. The percent of fractured faces has a substantial influence on the permeability of open-graded aggregate. For the same type of gradation, the aggregate with 100 percent fractured faces is more permeable than the aggregate with 88 percent fractured faces. For dense-graded aggregate, the difference in permeability due to fractured faces is not significant.
6. The percent of fractured faces has a significant influence on the resilient modulus of open-graded aggregate. For the same type of gradation, the aggregates with 100 percent fractured faces have a much higher resilient modulus than aggregates with 88 percent fractured faces. For dense-graded aggregates, the difference in the resilient modulus due to fractured faces is not obvious.

RECOMMENDATIONS

1. For pavement structural design with ATPM, a layer coefficient of 0.14 to 0.19 is recommended. A drainage coefficient of 1.15 to 1.25 is recommended.
2. The proposed gradation for FDAM is recommended for use. To ensure sufficient drainage and strength, 100 percent of the material retained above the ¼-in. sieve should be fractured on at least two faces. In locations in which this is not obtainable, 90 percent fracture on at least two faces should be specified. Where 100 percent fracture can be specified, a layer coefficient between 0.11 and 0.14 is recommended. Where 90 percent fracture is specified, a layer coefficient between 0.08 and 0.11 is recommended. The specific value may be determined knowing the anticipated stress in the aggregate.
3. A drainage coefficient of 1.05 to 1.15 is recommended for the FDAM with 100 percent of the material retained above the ¼-in. sieve fractured on two faces and 1.00 to 1.05 for 90 percent fractured on at least two faces.
4. A prime coat may be used on top of FDAM. This will make the FDAM material easier to run construction equipment on and more stable. However, it may reduce the permeability of FDAM. To reduce aggregate segregation, plant mix is recommended.

ACKNOWLEDGMENTS

The work in this paper was conducted as a part of a Highway Planning and Research project funded through FHWA, U.S. Department of Transportation, and Oregon Department of Transportation (ODOT). The authors are grateful for the support of the ODOT Pavements Unit and Pavement Services, Inc. The authors thank the ODOT Soils and Bituminous crews of the Materials Unit and Roger Miles, ODOT Pavements Unit; Amy Edwards, Pavements Unit; Gary Hicks, Oregon State University; and Scott Nodes, ODOT Research Unit.

REFERENCES

1. Cedergren, H. R. Why All Important Pavements Should Be Well Drained. Presented at 67th Annual Meeting of the Transportation Research Board, Washington, D.C., 1988.
2. Cook, M., and S. Dykins. Treated Permeable Base Offers Drainage, Stability. *Roads and Bridges*, May 1991, pp. 46–49.
3. Mathis, D. M. Permeable Bases Prolong Pavements, Studies Show. *Roads and Bridges*, Vol. 28, No. 5, May 1990, pp. 33–35.
4. Flynn, L. Open-Graded Base May Lengthen Pavement Life. *Roads and Bridges*, Sept. 1991, pp. 33–42.
5. *AASHTO Guide for Design of Pavement Structures*. AASHTO, Washington, D.C., 1986.
6. Forsyth, R. A. *Asphalt Treated Permeable Materials—Its Evolution and Application.* Quality Improvement Series QIP 117. National Asphalt Pavement Association, Lanham, Md. 1991.
7. *Drainage of Asphalt Pavement Structures*. Manual Series 15 (MS-15). The Asphalt Institute, College Park, Md., Sept. 1984.
8. Wells, G. K. *Determine Permeabilities of ATPB and CTPB Materials*. Report of Minor Research Project 631140-30019. California Department of Transportation, Sacramento, May 1986.
9. Mathis, D. M. *Design and Construction of Permeable Base Pavements*. FHWA, U.S. Department of Transportation, 1989.
10. Lovering, W. R., and H. R. Cedergren. Structural Section Drainage. *Proc., International Conference on the Structural Design of Asphalt Pavements*, Ann Arbor, Mich. 1962.
11. Hicks, R. G., L. E. Santucci, D. G. Fink, and R. Williamson. Effect of Laboratory Curing and Compaction Methods on the Stress Strain Behavior of Open-Graded Emulsion Mixes. Presented at the 58th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 1979.
12. Monismith, C. L., K. Wallac, E. Harm, and B. Unban. *Pavement Design Considerations for Two Layer Pavements Containing Open-Graded Asphalt Mixtures, Final Report*. University of California, Berkeley, 1982.
13. Rada, G. R., M. W. Witczak, and S. D. Rabinow. Comparison of AASHTO Structural Evaluation Techniques Using Non-Destructive Deflection Testing. In *Transportation Research Record 1207*, TRB, National Research Council, Washington, D.C., 1988.
14. Cedergren, H. R., K. H. O'Brien, and J. A. Arman. *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections*. Final Report (summary), Report FHWA-RD-72-30. FHWA, U.S. Department of Transportation, June 1972.
15. Hicks, R. G. *Factors Influencing the Resilient Properties of Granular Materials*. Ph.D. dissertation. University of California, Berkeley, 1970.
16. Hicks, R. G., and F. N. Finn. Analysis of Results from the Dynamic Measurements Program on the San Diego Test Road. *Proc., The Association of Asphalt Paving Technologists*, Vol. 39, 1970, pp. 153–185.
17. Allen, J. J. *The Effects of Non-Constant Lateral Pressures on the Resilient Response of Granular Materials*. Ph.D. dissertation. University of Illinois at Urbana-Champaign, 1973.
18. Kalcheff, I.V., and R. G. Hicks. A Test Procedure for Determining the Resilient Properties of Granular Materials. *Journal of Testing and Evaluation*, ASTM, Vol. 1, No. 6, 1973.

19. Boyce, J. R., S. F. Brown, and P. S. Pell. The Resilient Behavior of a Granular Materials Under Repeated Loading. *Proc., Australian Road Research Board*, 1976.
20. Monismith, C. L., J. A. Epps, D. A. Kasianchuk, and D. B. McLean. *Asphalt Mixture Behavior in Repeated Flexure*. Report TE 70-5. University of California, Berkeley, Jan. 1972.
21. Albright, S. *Evaluation of Crushed Aggregate Specifications Used by the Alaska Department of Transportation and Public Facilities.* M.S. thesis. Department of Civil Engineering, Oregon State University, Corvallis, 1986.
22. Zhou, H., and I. J. Huddleston. *Final Pavement Design Report: Fir Grove Lane–Towers Road Section Project.* Oregon State Highway Division, Salem, 1990.
23. Gower, J. L., and I. J. Huddleston. *Final Pavement Design Report: Rose Lodge–Polk County Line Project.* Oregon State Highway Division, Salem, 1989.
24. *Annual Book of ASTM Standards.* ASTM, Philadelphia, Pa., 1989.
25. Kozlov, G. S. *Improved Drainage and Frost Action Criteria for New Jersey Pavement Design, Volume III.* Report FHWA-NJ-84-015. FHWA, U.S. Department of Transportation, 1984.
26. *Laboratory Manual of Test Procedures.* Materials Section, Highway Division, Oregon Department of Transportation, Salem, 1986.
27. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing.* AASHTO, Washington, D.C., 1986.
28. Yoder, E. J., and M. W. Witczak. *Principles of Pavement Design*, 2nd ed. John Wiley and Sons, Inc., New York, 1975.

The contents of this paper reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the U.S. Department of Transportation or ODOT. Oregon does not endorse products of manufacturers. Trademarks or manufacturers' names appear herein only because they are considered essential to the object of this document. This paper does not constitute a standard, specification, or regulation.

Publication of this paper sponsored by Committee on Subsurface Drainage.