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Structural Properties of Laboratory Mixtures Containing Foamed Asphalt and Marginal Aggregates

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Four sands and one siliceous river gravel from various regions of Texas were stabilized with foamed asphalt to produce laboratory test specimens. The strength, stiffness, and stability of these specimens were measured by using common laboratory testing methods. The water susceptibility, temperature susceptibility, and fatigue performance of the asphalt paving mixtures were quantified. AASHO structural layer coefficients of the foamed asphalt were calculated and compared with those established for bituminous-stabilized bases at the AASHO Road Test. Equivalent thicknesses were determined for these foamed-asphalt mixtures. Based on available literature, foamed asphalt appears to be an economically attractive alternative for stabilization of pavement bases and subbases. However, laboratory results obtained in the study, which used marginal aggregates, suggest that foamed-asphalt mixtures have low stabilities and poor fatigue performance in comparison with conventional hot-mix paving materials. In addition, the foamed-asphalt mixtures have poor resistance to water deterioration.

The shortage of high-quality aggregates and increased traffic have created a need for treating local materials for use as base courses. Asphalt has become a common base stabilizer in the past 15 years; however, the criteria developed for materials selection and design and construction techniques have been based mainly on requirements developed for asphalt concrete surface courses. Thus, materials and construction techniques are being used that significantly increase cost and provide a stabilized material with properties that are superior to those required by traffic and the environment.

During the past 3 years, the Texas Transportation Institute has evaluated the use of more economical asphalt-treated bases. This research is sponsored by the FHWA and the Texas State Department of Highways and Public Transportation (TSDHPT). One method of producing economical bases or subbases that was evaluated is the stabilization of marginal aggregates with foamed asphalt.

The asphalt foaming process was first proposed by Csanyi (1,2) in the mid-1950s. The original process consisted of introducing steam into hot asphalt through a specially designed nozzle so that the asphalt was ejected as a foam (3). Because of the awkwardness of this process, the comparatively low cost of asphalt and energy, and the availability of quality aggregate, the process was not widely implemented until 1968 (4). Mobil Oil of Australia Ltd. developed methods to improve the production of foamed asphalt as well as mix design procedures. Continental Oil Company has further developed the process and has been licensed by Mobil Oil of Australia Ltd. to market the process in the United States.

The most important development has been the use of cold water with hot asphalt to produce foamed asphalt. A controlled flow of cold water is introduced into a hot asphalt stream, passed through a suitable mixing chamber, and then delivered through an appropriate nozzle as asphalt foam. Other recent advancements are improved foaming nozzles, development of admixtures to improve asphalt foam quality, and installation of field projects that have provided experience and enhanced progress in construction procedures.

In the past 10 years, the asphalt foaming process has been used successfully in Australia and more recently in South Africa in the stabilization of marginal-quality pavement materials.

The work described in this paper consists of laboratory testing of paving mixtures made with four sands and one siliceous gravel from various regions of Texas and stabilized with foamed asphalt. Testing included Hveem stability and resistance values, resilient modulus, tensile properties, water susceptibility, temperature susceptibility, and fatigue performance.

TEST PROGRAM

Laboratory experiments with paving mixtures containing foamed asphalt were conducted as described in Figures 1-3. Figure 1 shows a test program to determine the effects of asphalt cement content on the quality of mixtures and to aid in determining the optimum asphalt content. Figure 2 shows a more comprehensive program designed to determine comparative strength, stability, and water susceptibility of foamed-asphalt mixtures. Figure 3 depicts a sequence for testing the effects of flexural fatigue on foamed mixtures at the optimum asphalt content. Several of the tests performed throughout this program have been modified because of the atypical characteristics of the foamed-asphalt mixtures. Therefore, the results are useful for within-study comparisons and cannot be generally compared to published data. For example, Marshall and Hveem stabilities were conducted at 73°F (23°C) rather than at 140°F (60°C).

A laboratory model asphalt foaming apparatus (see Figure 4) furnished by Continental Oil Company in Ponca City, Oklahoma, was used to produce the foamed asphalt used in this study. The electrically powered device contains a 3-gal, temperature-controlled asphalt reservoir and is capable of measuring and mixing hot asphalt cement and atomized cold water with a specially designed nozzle to produce asphalt foam. Several days were required for the technical staff to become familiar with the foaming apparatus and its operation. During this period, a number of trials were conducted using various aggregates, aggregate moisture contents, asphalt-water mixture ratios, and asphalt cement temperatures.

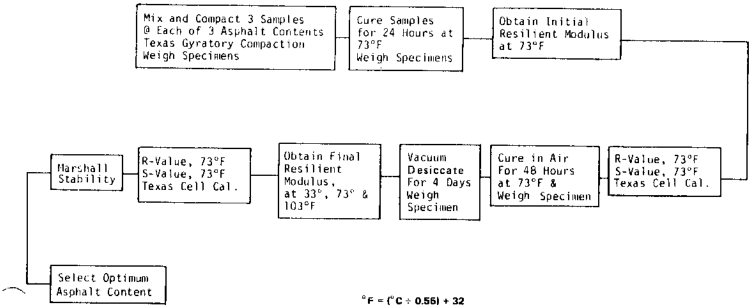
Before determination of the optimum asphalt content, a short experiment was performed to determine the temperature of the asphalt and the quantity of foaming water that would maximize the volume and duration of the asphalt foam. A chemical additive was also evaluated to determine its ability to counteract the defoaming action of any silicone that may have been added to the asphalt.

Based on this preliminary work, conditions were selected that produced all of the asphalt-aggregate mixtures discussed in this paper. Those conditions included an asphalt cement temperature of 325°F (163°C) with 2 percent water added to produce the foaming action and the addition of 0.25 percent of the chemical agent to improve foam quality. Optimum moisture content for mixing was determined to be about 8 percent for the sands and 5 percent for the subrounded river gravel.

MATERIALS

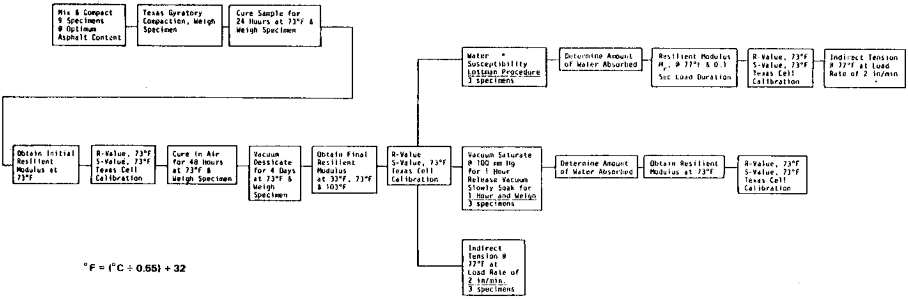
Six aggregates or combinations thereof were selected

Figure 1. Test program for selection of optimum asphalt content of foamed-asphalt test specimens.



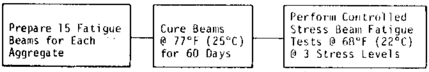
°F = (°C ÷ 0.55) + 32

Figure 2. Test program for foamed-asphalt specimens.



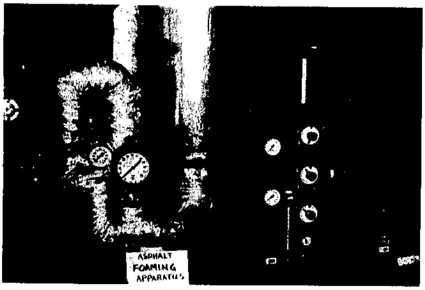
°F = (°C ÷ 0.55) + 32

Figure 3. Foamed-asphalt fatigue test program.



°F = (°C ÷ 0.55) + 32

Figure 4. Laboratory model foaming apparatus.



for use in this study. Five of the six aggregates were sands, and the other was a dense-graded gravel. A brief description of the aggregates is given below.

1. A subrounded, siliceous gravel was obtained from a Gifford-Hill plant near the Brazos River at College Station, Texas, in TSDHPT District 17. Standard sieves (ASTM E-11) were used to separate the aggregate into fractions sized from 0.75 in. (19 mm) to minus No. 200 (minus 0.075-mm) mesh. The various aggregate sizes were recombined according to the ASTM D3515-77 5A grading specification. This aggregate is a laboratory standard at the Texas A&M University materials laboratory (5).
2. A very clean, one-sized blow sand was obtained near Lubbock, Texas, in District 5.
3. A fairly well-graded field sand was obtained near Lufkin in District 11.
4. A typical sand was obtained from Padre Island in District 16.
5. An offshore beach-type sand with small quantities of organic matter was obtained near Port Isabel in District 21.
6. Silt from the Brazos River was sieved to obtain the minus No. 200 mesh material used to modify the sands from Districts 5 and 16.

The aggregates are identified here by the number of the district from which they were obtained. The laboratory standard aggregate is labeled LS.

An AC-10 asphalt cement was obtained from the American Petrofina refinery located near Mount Pleasant, Texas. This asphalt is used as the laboratory standard at the Texas A&M University materials laboratory (5). A foaming agent produced by Continental Oil Company was used to aid the foaming action of the asphalt.

DETERMINATION OF OPTIMUM ASPHALT CONTENT

The test program shown in Figure 1 was used to determine the optimum foamed-asphalt content for each of the aggregates studied.

After several trials with various moisture contents, an optimum moisture content for mixing and compaction was determined for each of the aggregates. The moisture content referred to as the fluff point (6), which represents the state in which a given weight of soil has its maximum loose bulk volume, was attempted as a first trial. However, additional wetting of these aggregates appeared to improve dispersion of the foamed asphalt during mixing. This additional water increased the moisture content above the optimum for compaction. Therefore, the mixtures were set aside for about 20 min and periodically stirred to allow evaporation of some of the moisture. Three specimens of each of the three asphalt contents were mixed by using foamed asphalt from the asphalt foaming apparatus and the dampened aggregates. Test specimens were compacted at room temperature [approximately 77°F (25°C)] or in accordance with TSDHPT test method TEX-206-F, Part II.

The specimens were extracted from the mold and allowed to cure 24 hr at room temperature. After initial testing, the specimens were allowed to cure an additional 48 hr and were then placed in a vacuum desiccator for 4 days. After being removed from the desiccator, the specimens were subjected to the final phase of testing as shown in Figure 1.

STRUCTURAL EVALUATION OF FOAMED-ASPHALT MIXTURES

The foamed-asphalt mixtures were evaluated in terms of their ability to perform as part of a structural pavement system. All characterization was based on mixtures at optimum percentages of foamed asphalt. The structural evaluation is based on the results of diametral resilient modulus versus temperature, beam flexural fatigue, and Hveem stability.

Resilient modulus data are necessary to characterize these materials in a layered elastic model of the pavement system. The BISAR multilayered elastic computer program (7) and the Chevron stress-sensitive layered elastic program, PSAD2A (8), were used to model the pavement systems. Flexural beam fatigue data were used to establish a failure criterion. This fatigue failure criterion was used together with other mechanistic responses to evaluate the performance potential of foamed-asphalt mixtures.

Stability tests were used to evaluate the ability of the foamed asphalt to resist shearing stresses.

Resilient Modulus Versus Temperature

One of the most successful ways to screen potential pavement structural materials has been to determine the resilient modulus of the material over the range of temperatures expected to be encountered in the pavement system. The Schmidt diametral resilient modulus device (9) was used for this purpose. Foamed-asphalt mixtures were tested at 32°, 73°, and 104°F (0°, 23°, and 50°C). This range in temperature should represent the range developed in most asphalt bases in Texas. Although pavement temperatures in uppermost asphalt concrete layers may approach 140°F (60°C), using the Schmidt device to test resilient modulus at these high temperatures is impractical. The time of loading in the diametral resilient modulus test is 0.10 sec, which is representative of the duration of moving wheel loads.

When the resilient modulus is known for the loading condition and temperature expected in the field, the layered elastic pavement model becomes a valuable analytic tool for calculating and analyzing mechanistic responses.

Figure 5 summarizes the results of resilient modulus versus temperature for foamed-asphalt materials and compares these responses with those of other asphalt mixtures commonly used in Texas. Although the moduli of the foamed-asphalt materials at temperatures exceeding 90°F (32°C) are quite low, the moduli produced may be adequate for bases or improved subgrades because the temperatures developed in these layers are usually below 90°F (32°C).

Potential as Base Material

Three criteria affect the potential of foamed asphalt as a structural base course or a structural full-depth layer: (a) distribution of vertical stresses, (b) resistance to shearing failure, and (c) fatigue life characteristics.

An effective base material in a flexible pavement system spreads the load applied at the surface so that shear and consolidation deformation will not occur in the subgrade. It is evident from layered elastic theory that the greater the ratio of the elastic modulus of the reinforcing layer to that of the supporting layer (E_1/E_2), the greater the success in distributing stress. As the E_1/E_2 ratio becomes greater, the vertical stress gradient with depth increases negatively. The fundamental equilibrium equations of layered elastic theory illustrate that a negative vertical stress gradient must be accompanied by an equally high positive shear stress gradient.

As a consequence of the increase in the reinforcing action of the reinforcing layer with increasing E_1/E_2 ratios, the shear stresses in the reinforcing layer build up and become critical. Thus, a base reinforcing layer or a full-depth reinforcing layer must not only have an effectively high E_1 to distribute stresses effectively but must also possess satisfactorily high shear resistance to maintain its own structural integrity. Of course, the shear stress levels within the reinforcing layer are substantially reduced by increasing the thickness of the reinforcing layer.

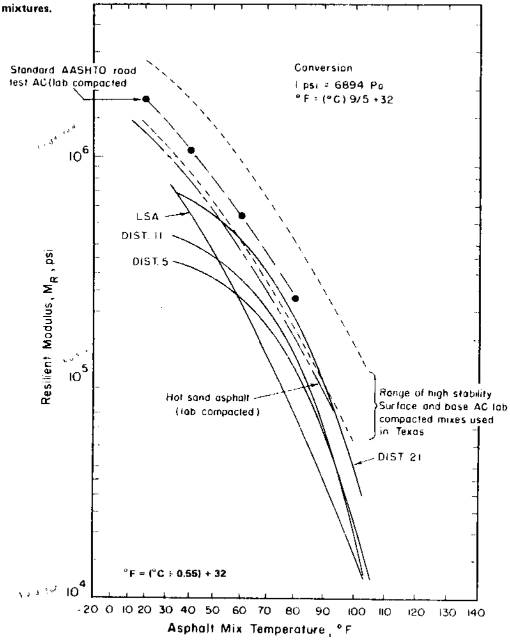
A third criterion for acceptable performance of an asphalt-stabilized base or a full-depth asphalt-stabilized pavement is acceptable fatigue life characteristics.

The potential of foamed asphalt as a structural base course or a structural full-depth layer, based on these three requirements, is discussed below.

Distribution of Vertical Stresses

The relative ability of foamed asphalts to distribute vertical stresses and thus reduce critical subgrade strains or subgrade deflections can be assessed by comparing curves for M_R versus temperature. However, to illustrate this ability more vividly, the foamed asphalt was compared with the high-quality asphalt-stabilized base materials used at the AASHTO Road Test. The comparison was made by using two methods. First, AASHO structural layer coefficients of the foamed asphalt were calculated and compared with those established for bituminous-

Figure 5. M_R **versus temperature for foamed-asphalt mixtures.**



stabilized bases at the AASHO Road Test. Second, equivalent thicknesses of foamed asphalt and a quality emulsion-stabilized base material were evaluated. The limiting criterion here was vertical subgrade deflection.

No material has a unique structural layer coefficient, but the structural coefficient of any pavement material may change as a function of such factors as pavement temperature, surrounding layer thicknesses, loading intensities, and moisture changes in the subgrade and other unbound layers. The AASHO structural coefficients are nothing more than coefficients of a regression equation that relates the effect of certain specific pavement layers to pavement performance. Thus, an evaluation of the relative performance of pavement materials used at the AASHO Road Test is possible.

Because the AASHO materials have been characterized in terms of their elastic properties (resilient modulus and Poisson's ratio), layered elastic models can be used to make a mechanistic evaluation of AASHO test sections. Furthermore, the elastic properties of foamed-asphalt mixtures can be substituted for those of selected layers in the AASHO layered elastic models, and the changes in critical pavement mechanistic responses caused by this substitution can be evaluated. The result is that the critical mechanistic responses of foamed-asphalt can be compared with the performance of other base materials as has been empirically established at the AASHO Road Test.

The PSAD2A stress-sensitive layered elastic computer program was selected to model the AASHO pavement sections (loop 4). The AASHO materials were characterized elastically based on the work of Finn and others (10). The methodology used to develop the structural layer, a_2, coefficients is discussed in detail by Little and Epps (11). The criterion on which the structural layer coefficients are based is vertical subgrade deformation.

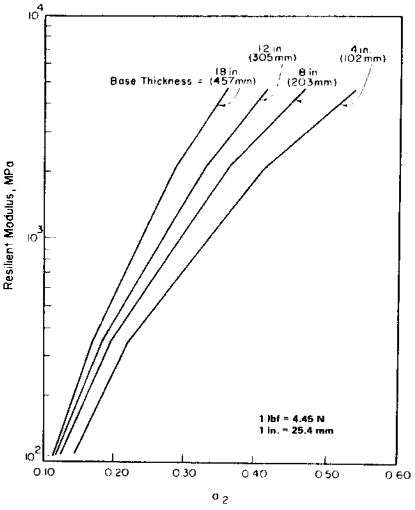
Results of numerous runs of the relatively expensive PSAD2A program used to develop a_2's for various resilient moduli values are summarized in Figure 6. Note the tremendous effect of base thickness on a_2.

The a_2 values derived from this analysis are summarized in Table 1. It is important to point out that these values should be used only for comparative purposes and not for design. More detailed testing on mixture variable effects must be completed before layer coefficients can be used for design purposes, and even then they must be used with sound judgment. The a_2 derived for a base thickness of 12 in. (30 cm) represents the value best suited for comparison with the single AASHO value.

The a_2 values presented in Table 1 are for two weighted average annual temperatures: 68° and 82°F (20° and 28°C). These represent extremes in weighted annual pavement temperatures. The weighted average annual pavement temperature of 68°F represents Ottawa, Illinois, which is near the site of the AASHO Road Test. The weighted average annual pavement temperature of 82°F represents Houston, Texas. These extremes are presented to illustrate the effect of location and climatic conditions on the structural coefficient.

The 1972 AASHTO Interim Guide for Flexible Pavement Design (12) can be used to illustrate further the significance of the structural coefficient with respect to the performance of the pavement system. The performance life of a typical Texas farm-to-market roadway can be calculated by using the structural coefficients in Table 1. Figure 7 shows the results of the analysis. The essence of this analysis is that pavement performance is severely affected by the smaller structural coefficients, and the resulting pavement lives are inadequate.

Figure 6. Average annual resilient modulus versus structural coefficient a_2.



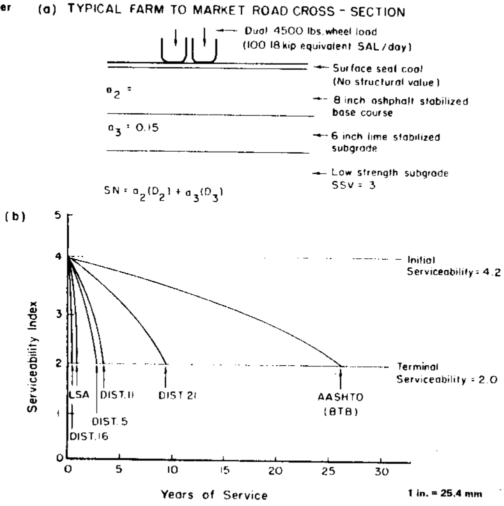
Perhaps a more rational scheme for comparing the ability of foamed asphalt and high-quality asphalt-stabilized bases to dissipate vertical compressive subgrade stresses is to compute equivalent thicknesses of these layers based on the criterion of vertical subgrade compressive strain (ϵ_v). The procedure for this computation is shown in Figure 8. The Chevron multilayered elastic computer program was used to compute the maximum ϵ_v under a dual 4,500-lb wheel load. Because the resilient

Table 1. Structural layer coefficients computed for foamed-asphalt materials.

Mixture	Weighted Annual Pavement Temperature (°F)	Structural Layer Coefficient for Base-Course Thickness				
		4 in.	8 in.	12 in.	18 in.	Avg
District 5	68	0.34	0.29	0.27	0.24	0.28
	82	0.26	0.22	0.20	0.18	0.21
District 11	68	0.35	0.31	0.29	0.25	0.30
	82	0.27	0.23	0.21	0.19	0.22
District 16	68	0.29	0.25	0.23	0.21	0.24
	82	0.21	0.17	0.15	0.14	0.17
District 21	68	0.42	0.37	0.34	0.29	0.35
	82	0.32	0.28	0.26	0.22	0.27
LSA	68	0.30	0.26	0.24	0.22	0.25
	82	0.22	0.18	0.17	0.15	0.18
AASHTO-high quality bituminous-stabilized base	68	0.44	0.39	0.35	0.31	0.37
	82	0.39	0.34	0.30	0.26	0.32

Note: °F = (°C ÷ 0.55) + 32; 1 in. = 25.4 mm.

Figure 7. Effect on performance life of variation in structural layer coefficient.

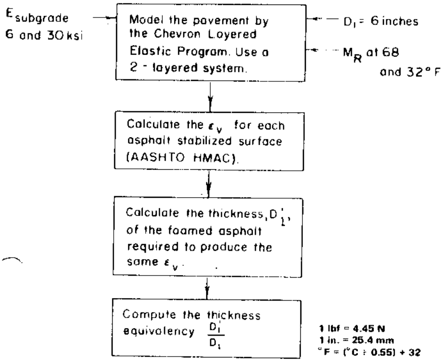


moduli of the materials in question change with temperature, the analysis scheme encompassed equivalent thickness calculations at several pavement temperatures and reinforcing layer thicknesses and over several strengths of subgrade. The results are summarized in Table 2.

The thickness equivalencies based on subgrade vertical compressive strain are in reasonable agreement with the structural coefficients calculated previously. These equivalencies indicate that, if vertical subgrade compressive strain is the sole performance criterion, the following approximate thicknesses of foamed asphalt containing each type of aggregate would be required to equal 1.0 in. of high-quality HMAC base:

Aggregate	Avg. Equivalent Thickness (in.)
District 5	1.6
District 11	1.52
District 16	1.84
District 21	1.22
LSA	1.94

Figure 8. Procedure used to develop thickness equivalency ratios based on vertical subgrade strain criterion.



1 lbf = 4.45 N
1 in. = 25.4 mm
°F = (°C ÷ 0.55) + 32

Resistance to Shearing Failure

As previously mentioned, the shearing stresses induced in the reinforcing layer of a pavement section increase as the modular ratio E_1/E_2 increases and as the a/D_1 ratio increases (i.e., thin pavements). If full-depth pavements are considered or if the surface and stabilized base are included in the reinforcing layer, it becomes evident that shearing stresses may become critical in the reinforcing layer, particularly for thin pavements with high E_1/E_2 ratios.

The Hveem stability test and the resistance test are widely used to evaluate the stability of pavement materials. These tests are primarily a measure of the lateral pressure induced in the closed test system due to an applied vertical pressure. Thus, these tests are indirect indicators of the ability of the pavement materials to handle the high shearing stresses that may develop in a pavement. Repeated- and static-load triaxial tests would provide a better indication of shear strength. However, these tests were not part of this program.

Table 3 summarizes the Hveem stabilities (S-values) calculated for the mixtures evaluated. The resistance value (R-value) is acceptable for all but one mixture before vacuum saturation but is unacceptable for most after vacuum saturation. The S-value was measured at 73°F (23°C) instead of 140°F (60°C) as for surface courses. This is considered an acceptable procedure by several state agencies in the evaluation of base materials.

It must be concluded based on these results that these mixtures are at best marginally acceptable in terms of resistance to lateral flow after moisture conditioning.

Fatigue Life Characteristics

Controlled stress beam fatigue tests were performed using foamed asphalt mixtures containing the aggregates from Districts 5, 11, and 21 and the LS aggregate. Five specimens were tested at each of three stress levels. The results of the fatigue tests are summarized in Table 4 in the form of the well-known relation between load applications to failure (N_f) and initial bending strain (ε), where

$$N_f = K_1 (1/\varepsilon)^{n_1} \tag{1}$$

Also given in Table 4 are K_1 and n_1 regression constants developed for typical laboratory con-

Table 2. Thickness equivalencies based on vertical subgrade strain criterion.

Foamed Asphalt	D_1 (in.)	Temperature (°F)	E_{subgr} (psi 000s)	$\varepsilon_v \times 10^{-6}$	D_1' (in.)	D_1'/D_1
District 5	6	68	3	780	9.93	1.65
			30	340	9.30	1.55
		82	3	1,110	10.00	1.67
			30	445	9.10	1.51
District 11	6	68	3	730	9.20	1.53
			30	340	9.00	1.50
		82	3	1,110	9.60	1.60
			30	445	8.75	1.46
District 16	6	68	3	780	10.87	1.81
			30	340	10.00	1.67
		82	3	1,110	12.84	2.14
			30	445	10.31	1.72
District 21	6	68	3	780	7.09	1.18
			30	340	6.94	1.16
		82	3	1,110	7.75	1.29
			30	445	7.63	1.27
LSA	6	68	3	780	12.00	2.00
			30	340	10.85	1.81
		82	3	1,110	12.98	2.16
			30	445	10.69	1.78

Note: 1 in. = 25.4 mm; °F = (°C ÷ 0.55) + 32.

Table 3. Evaluation of 73°F Hveem stability and resistance values after curing and moisture treatment.

	S-Value		R-Value		R-Value Acceptibility	
Aggregate	Before Soak	After Soak	Before Soak	After Soak	Before Soak	After Soak[a]
LS	53	35	94	95	Yes	Yes
District 11	49	20	94	78	Yes	Yes
District 5 + silt	43	D	92	D	Yes	No
District 21	41	D	93	D	Yes	No
District 5	30	D	88	D	Yes	No
District 16 + silt	31	D	86	D	Yes	No
District 16	23	D	74	D	No	No

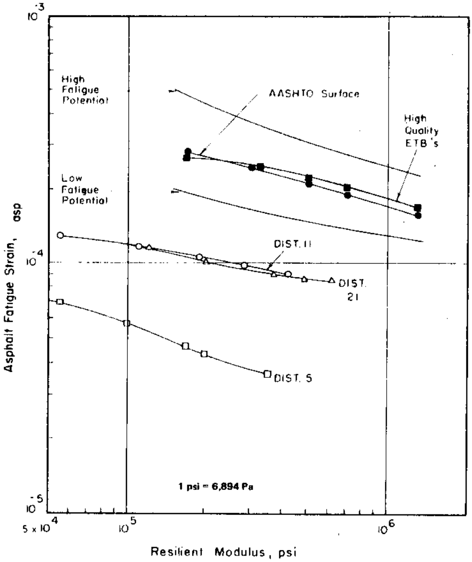
Note: D = disintegrated.

[a] The R-value criterion is 78 for a base course after vacuum saturation.

Table 4. Results of laboratory controlled stress beam fatigue testing at 68°F.

Material	K_1	n_1	R^2
District 5	9.02×10^{-6}	2.290	0.94
District 11	4.476×10^{-15}	4.831	0.92
District 21	6.395×10^{-17}	5.229	0.74
LS	4.717×10^{-3}	1.753	0.79
AC base, Colorado (13)	2.01×10^{-5}	2.69	-
Sand base, Colorado (13)	8.97×10^{-7}	3.25	-
Asphalt-treated base (emulsion), California (13)	9.19×10^{-7}	3.15	-
Granite-stabilized with 6 percent asphalt cement (14)	6.11×10^{-6}	3.38	-
30 percent crushed rock, 53 percent sand, 9 percent limestone, 8 percent asphalt cement (14)	8.8×10^{-15}	5.1	-
Fine granite, 6 percent asphalt cement, California (14)	8.91×10^{-7}	2.95	-

Figure 9. Permissible asphalt strain as a function of resilient modulus of mixture (based on 1 million strain repetitions).



trolled stress fatigue testing of various types of potential base-course materials.

It is obvious that the fatigue properties of the foamed-asphalt mixtures composed of District 21 and District 11 aggregates were the only ones to exhibit competitive values in comparison with traditional asphalt-stabilized highway materials. In order to evaluate the specific implications of fatigue properties of these mixtures, they will be further dis-

Figure 9 offers a vivid illustration of the fatigue potential of the foamed-asphalt mixtures in comparison with other conventionally used highway materials. The plots in this figure are unique in that they present the total fatigue picture of a material for a given life in terms of load repetitions to failure. The life selected in the comparative analysis of Figure 9 is 1 million repetitions. Each point identifying the respective curves describes the relation between allowable asphalt fatigue strain and resilient modulus of the mix for a fatigue life of 1 million repetitions.

For purposes of comparison, all curves in Figure 8 have been shifted to the right to approximate field effects. The AASHO and foamed-asphalt curves were shifted by a factor of about 13 as advocated by Finn and others (15) for AASHO Road Test conditions.

The fatigue potential of the foamed-asphalt mixtures is well below that of the AASHO mixtures and the good-quality emulsion-stabilized bases. Foamed asphalts are also substantially below the line of low fatigue potential.

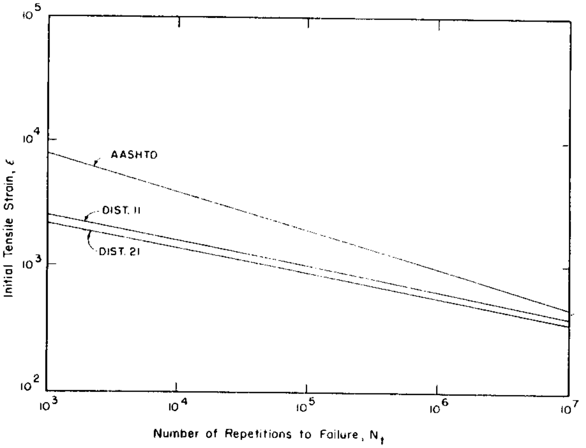


Figure 10. Laboratory fatigue curves at 68°F used as failure criteria.

Thickness Equivalencies Based on Fatigue

Thickness equivalencies for the two foamed-asphalt mixtures composed of aggregates from District 11 and District 21 were calculated based on a fatigue failure criterion. The fatigue curves in Figure 10 for Districts 11 and 21 foamed asphalt supplied the failure criterion, and fatigue curves developed by Finn and others (15) from laboratory tests of the asphalt-stabilized materials used at the AASHO Road Test formed the control failure criterion.

The asphalt-bound AASHO materials characterized by Finn and others are typical of those used to construct high-quality surface and binder courses at the AASHO Road Test. However, the fatigue properties of these AASHO materials are inferior to many other materials found in the literature. These fatigue curves, however, when shifted to the right to account for beneficial field effects, correspond well with field-shifted asphalt and emulsified-asphalt fatigue curves developed by Santucci (16). In addition, the development of the curves derived by Finn and others is well-documented and provides for temperature or elastic modulus shifts in the curves, which were also evaluated.

The general equation characterizing the fatigue performance of the AASHO materials as developed by Finn and others (15) is

$$\log N_f = 14.32 - 3.291 \log(\epsilon/10^{-6}) - 0.354 \log(E/10^3) \qquad (2)$$

where ε is maximum tensile strain at the bottom of the asphalt layer and E is the elastic modulus of the asphalt layer.

The general procedure was to compare the respective foamed-asphalt mixtures with the AASHO asphalt-bound materials based on their fatigue properties. The index of comparison is a thickness equivalency ratio. The procedure is shown in Figure 11. The BISAR program was used to model the pavement structures analyzed. Fatigue characteristics, resilient moduli versus temperature, and fatigue-curve/temperature shift factors are summarized in Table 5.

Tables 6 and 7 summarize the results of the fatigue-based thickness equivalencies. It is obvious from the general magnitude of these thickness equivalencies that the foamed asphalts are insufficient structurally unless used in thickness two to four times greater than that of good-quality, full-depth asphalt concrete.

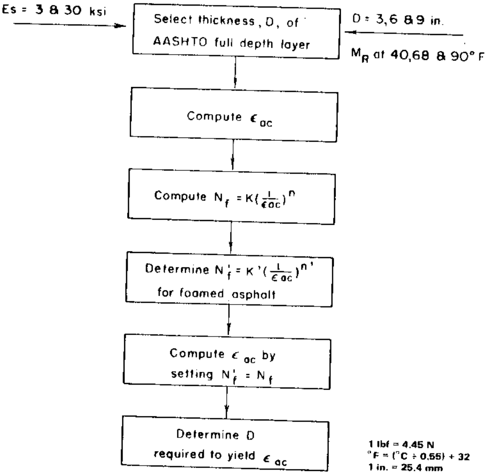
The fact that thickness equivalencies are a function of the geometrics of the pavement cross section, stiffness of the subgrade, and stress distribution in the system is indicated in Tables 6 and 7.

CONCLUSIONS

Four sands and one siliceous river gravel from various regions of the state of Texas were used in the laboratory to prepare paving mixtures with foamed asphalt. The following conclusions are based on laboratory tests on these mixtures.

1. Foamed asphalt may be an economic alternative for stabilization of pavement layers. Only carefully monitored field installations using appropriate mixture designs and construction procedures can provide the desired assurance.
2. Paving mixtures containing foamed asphalt are superior to unbound materials in terms of vertical stress distribution.
3. Laboratory specimens tested in this study were highly susceptible to moisture deterioration.
4. Mixture stabilities were comparatively low but may be acceptable in bases or subbases if moisture susceptibility can be improved.
5. The foamed-asphalt mixtures studied exhibited comparatively short fatigue lives but may be acceptable in base or subbase layers in a pavement system.
6. Engineering properties of poorly graded sands stabilized with foamed asphalt may be improved by the addition of minus No. 200 (minus 0.075-mm) mesh material.
7. Foamed-asphalt mixtures would be satisfactory for in-place stabilization of existing subgrade material to reduce the thickness requirements of higher-quality asphalt-stabilized bases.
8. Only a well-graded sand (such as that from District 11) or higher-quality aggregate would be acceptable for full-depth paving with foamed asphalt.

Figure 11. Procedure for computing thickness equivalency ratios based on maximum tensile strain in asphalt concrete.



1 lbf = 4.45 N
°F = (°C ÷ 0.55) + 32
1 in. = 25.4 mm

Table 5. Fatigue parameters used to develop failure criteria for calculating thickness equivalencies.

Material	Temperature (°F)	Resilient Modulus (psi 000s)	Fatigue Curve Shift Factor from 68°F	Fatigue Life Equation
AASHTO	68	500	-	$\log N_f = 14.82 - 3.291 \log(\epsilon/10^{-6}) - 9.5854 \log(E/10^3)$
	40	1,300	0.44	
	90	170	2.51	
District 11	68	190	-	$N_f = 4.476 \times 10^5 (1/\epsilon)^{4.831}$
	40	420	0.51	$N_f = 2.283 \times 10^{-15} (1/\epsilon)^{4.831}$
	90	55	2.88	$N_f = 1.289 \times 10^{-14} (1/\epsilon)^{4.831}$
District 21	68	370	-	$N_f = 6.395 \times 10^{-17} (1/\epsilon)^{5.229}$
	40	630	0.63	$N_f = 4.029 \times 10^{-17} (1/\epsilon)^{5.229}$
	90	120	2.62	$N_f = 1.675 \times 10^{-16} (1/\epsilon)^{5.229}$

Note: °F = (°C ÷ 0.55) + 32; 1 psi = 6,895 Pa.

Table 6. Thickness equivalencies based on fatigue failure criteria for District 11.

Thickness of Asphalt Structural Layer, D_1 (in.)	Pavement Temperature (°F)	E_{subgr} (psi 000s)	Equivalent Thickness of Foamed Asphalt, D_1 (in.)	Equivalent Thickness Ratio, D_1/D_2
3	40	3	10.71	3.57
		30	10.60	3.53
	68	3	11.75	3.92
		30	11.73	3.91
	90	3	-	-
		30	-	-
6	40	3	16.15	2.69
		30	15.00	2.50
	68	3	17.00	2.83
		30	15.50	2.58
	90	3	-	-
		30	21.00	3.50
9	40	3	24.75	2.75
		30	18.00	2.00
	68	3	21.00	2.33
		30	18.10	2.01
	90	3	-	-
		30	21.00	2.33

Note: °F = (°C ÷ 0.55) + 32; 1 psi = 6,894 Pa.

Table 7. Thickness equivalencies based on fatigue failure criteria for District 21.

Thickness of Asphalt Structural Layer, D_1 (in.)	Pavement Temperature (°F)	E_{subgr} (psi 000s)	Equivalent Thickness of Foamed Asphalt, D_1 (in.)	Thickness Ratio D_1/D_2
3	40	3	8.90	2.97
		30	8.65	2.88
	68	3	8.80	2.93
		30	8.53	2.84
	90	3	-	-
		30	12.00	4.00
6	40	3	12.63	2.10
		30	12.00	2.00
	68	3	12.91	2.15
		30	12.10	2.02
	90	3	16.76	2.79
		30	15.20	2.53
9	40	3	18.00	2.00
		30	13.00	1.44
	68	3	16.55	1.84
		30	15.00	1.67
	90	3	20.00	2.22
		30	17.75	1.97

Note: °F = (°C ÷ 0.55) + 32; 1 psi = 6,894 Pa.

It should be emphasized at this point that the aggregates selected for use in this study are marginal and thus difficult to stabilize and that much greater success with foamed asphalt has been reported elsewhere in the literature. The asphalt cement used in this study may have contained a silicone antifoaming additive. As a result, the comparatively short half-life of the asphalt foam may have impeded thorough mixing with the aggregates.

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Sprinkle Treatment in Illinois

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Three sprinkle treatment projects built in Illinois in 1980 and 1981 have been evaluated by using accident data, friction measurements, texture measurements, chip counts, and visual observations. This construction technique of applying a precoated chip to a freshly placed asphaltic concrete mat has proved to be a practical, economical method for providing a high-macrotexture, high-friction mat that should reduce accidents.

Sprinkle treatment is a method that provides a safe riding surface by using a minimum amount of high-quality aggregates, which may be limited in supply and often expensive. This is achieved by sprinkling a precoated chip and rolling it into a freshly placed asphaltic concrete mat.

Three projects are involved in this research study, the oldest of which is about 2 years old. Varying chip spread rates, types of chips, and types of topography have been involved in the three projects. The projects are being evaluated by using friction, texture, and chip count measurements. Visual observations were made during construction and will continue to be made to evaluate performance. Traffic accident analyses both before and after sprinkle treatment have been made for one project constructed 19 months ago.

FIELD TEST PROGRAM

The first sprinkle treatment project built in Illinois is located on US-151/IL-35 from East Dubuque to the Illinois-Wisconsin line. The job is 1.93 miles long and was completed during August 1980. The average daily traffic (ADT) on the route is 8,600 vehicles, including 1,250 commercial vehicles in two lanes. IL-35 in this area is winding and hilly, and there is a third truck lane for about a quarter of a mile. Accident experience on this roadway had been a cause for concern and was the primary reason for placing the sprinkle treatment.

The second project is located on IL-185 from US-40 near Vandalia northwesterly to the Fayette-Montgomery County line. This project was done with both financial and technical assistance from Region 15 of the Demonstration Projects Division of FHWA. IL-185 carries an ADT of 1,300 to 1,600 over most of the project, and the mile nearest Vandalia carries