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16. Abstract

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AASHTO structural layer coefficients of the foamed asphalt were calculated and compared to those established for bituminous stabilized bases at the AASHTO 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 this study, utilizing marginal aggregates, suggest that foamed asphalt mixtures have low stabilities and poor fatigue performance when compared to conventional hot mix paving materials. In addition, the foamed asphalt mixtures have poor resistance to water susceptibility.

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STABILIZATION OF MARGINAL AGGREGATES
WITH
FOAMED ASPHALT

by

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Research Report Number 235-1

Sponsored by

Texas State Department of Highways and Public Transportation
in Cooperation with the
U. S. Department of Transportation
Federal Highway Administration

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

ABSTRACT

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IMPLEMENTATION STATEMENT

The use of foamed asphalt to stabilize cold, wet, fine-grained aggregates appears to be an economically attractive alternative for the preparation of selected pavement layers. A higher probability of success should be anticipated when the material is employed in dry climates over well-drained soils.

Presently, field application of foamed asphalt mixtures should be considered experimental. Large-scale use of the product on State maintained routes is not recommended. The most beneficial use of foamed asphalt at this time appears to be for stabilization of low-volume or county roads.

ACKNOWLEDGMENTS

Dr. Robert E. Long of the Texas SDHPT and Mr. Ray Hurst of the FHWA served as contact representatives for research study 235.

A laboratory model asphalt foaming apparatus was provided by Continental Oil Company (Conoco) of Ponca City, Oklahoma. Mr. P. Jay Ruckel of Conoco provided guidance and training in the operation of the asphalt foaming device and preparation of the foamed asphalt mixtures.

Mr. C. E. Schlieker conducted the bulk of the laboratory testing with the assistance of Messrs. Ed Ellis and Sidney Greer.

Typing of the manuscript was performed by Mmes. Emily Arizola and Bea Cullen.

The efforts of these individuals are gratefully acknowledged.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

INTRODUCTION

The shortage of high quality aggregates together with increased traffic has created a need for treating local materials for use as base courses. Asphalt has become a common base stabilizer in the last fifteen 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, because of these sometimes "strict" requirements, materials and construction techniques are being utilized which significantly increase cost and provide a stabilized material whose properties are in excess of those required by traffic and the environment.

This report is the first of a series that will result from Research Study Number 235. The objective of this study is to provide the technology for the utilization of more economical asphalt treated bases. This report deals specifically with the stabilization of marginal aggregates using foamed asphalt.

The asphalt foaming process was first proposed by Csanyi (1, 2) in the mid-1950's. The original process consisted of introducing steam into hot asphalt through a specially designed nozzle such that the asphalt was ejected as a foam (3). Due to the awkwardness of this process, the comparatively low cost of asphalt and energy and availability of quality aggregate, the process was not implemented until 1968 (4). Mobil Oil Australia 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 Australia 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 (5). 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 involve improved foaming nozzles, development of admixtures to improve asphalt foam quality and installation of field projects which 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 for stabilization of marginal quality pavement materials. Installations in the United States are located in Arizona, Colorado, North Dakota and Oklahoma and range up to 20 years in age.

This report discusses laboratory testing of paving mixtures made with four sands and one siliceous gravel from various region of Texas and stabilized with foamed asphalt. Testing procedures include Hveem stability and resistance values, resilient modulus, tensile properties, water susceptibility, temperature susceptibility and fatigue performance.

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 this study, using marginal aggregates, suggest that foamed asphalt mixtures have low stabilities and poor fatigue performance when compared to conventional hot mix paving materials. In addition, the foamed asphalt mixtures are highly susceptible to moisture deterioration.

Field trials using paving mixtures stabilized with foamed asphalt can provide a wealth of information to evaluate marginal materials as well as provide experience in working with this relatively new product.

REVIEW OF EXISTING INFORMATION

Foamed asphalt is produced by combining, under a controlled process, a small quantity of water with a hot penetration grade binder. The foamed asphalt produced forms a unique binder in the stabilization process which allows intimate mixing with cold, moist aggregates. The mixing of the foamed asphalt with the aggregates may take place either in situ or in a central plant.

Foamed asphalt relies on the well known phenomenon that a small volume of water added to hot asphalt yields an immense volume of foamed asphalt. Typically, 1 part of water and 50 parts of hot asphalt cement expand into foamed asphalt with a ten to fifteen-fold volume increase (6). Properties of the foamed asphalt include a low apparent viscosity, subtantial increase in surface area and a change in surface or interfacial tension (6). These properties enable foamed asphalt to coat moist, cold aggregate surfaces, particularly, the "fines" fraction.

ECONOMICS

Economic benefits may result from the use of low cost locally available aggregates and also from the possible reduction in total thickness of the pavement structure. Furthermore, the foamed asphalt process may prove ideal for upgrading many miles of unsurfaced roads, prior to surfacing, by in situ stabilization of the base.

Foamed asphalt is economically advantageous in that the process is relatively simple and does not require major investments in equipment.

Lower energy use and the use of marginal aggregates are economically as well as ecologically beneficial. Binder costs are not increased by diluents and additional manufacturing costs. Transportation costs may be less since no diluents as in cutbacks or water as in emulsion need be hauled from the source to the mixing plant (7).

Since foamed asphalt can be compacted immediately following mixing, lengthly traffic delays are averted. This may be a significant economic as well as convenience benefit to the user.

The foamed asphalt process appears to be particularly well suited for low volume roads in rural areas where transportation and implementation costs prohibit the use of hot mix, or where the availability of inexpensive yet suitable aggregates provide an economic advantage (8).

MATERIAL CHARACTERISTICS

Materials characterization of foamed asphalts is just beginning. However, sufficient data are currently available to evaluate the potential for foamed asphalt.

Perhaps the most detailed rheological study and dynamic modulus testing of foamed asphalts was done by Majidzadeh (9). Based on the dynamic moduli of three foamed asphalt mixtures and one emulsion stabilized mixture, thickness equivalency ratios were proposed. Interestingly enough, the foamed mixtures appeared to out perform the emulsified asphalt mix by a factor of about two (9). These thickness equivalencies were, however, developed without a failure criterion. Thus, the layer thickness equivalency evaluation was limited to simulation of non-failure related responses of the pavement.

Thickness equivalencies, strength coefficients or any measure of the comparative ability of a material to contribute to pavement system performance must be evaluated carefully by the user. These equivalency indices may be developed based on actual field performance, full scale field testing, theoretical calculation based on elastic or viscoelastic layered theory or correlations between specific test properties and actual performance. No matter how the equivalency indices are determined, there are always strict limitations in their usage due to the interdependency of the materials in the pavement system. In essence, there is no unique layer thickness equivalency or structural coefficient. However, when the user understands the criteria for development and limitations of these coefficients, they become valuable indices of comparative performance.

The thickness equivalencies developed by Majidzadeh (9) were based on the relative ability of the foamed asphalt mixes to dissipate maximum tensile strains at the bottom of the full depth AC section (surface plus foamed base) compared to an emulsified asphalt mix. Pavement sections were modeled using layered elastic theory.

Bowering (10) developed "relative thickness coefficients" based on the cohesiometer test evaluation of "gravel equivalency". This procedure is part of the California Method of flexible pavement design (11). Based on these criteria, Bowering and Martin found that 1.4 to 1.7 inches of foam treated material is equivalent to 1.0 inches of conventional asphalt base.

Abel and Hines (12) calculated AASHTO type strength coefficients for foamed asphalt mixes. Actually, the strength coefficients were developed from a layered elastic analysis based on the equivalent thickness of foamed asphalt required to produce a maximum tensile strain in the bottom of the full depth AC layer (surface plus foamed asphalt) equal to that produced in a full depth hot mix layer. These coefficients ranged from 0.12 to 0.34. The low value was for a foamed asphalt mixture using poorly graded, low shearing strength silty gravel. The high coefficient, 0.34, was computed for a foamed asphalt mixture using an A-2-4 soil-aggregate. The high coefficient for the A-2-4 soil-aggregate indicates an excellent potential for foamed asphalt for in situ base stabilization of native soils.

Repeated load triaxial testing and resilient modulus testing using the diametral resilient modulus device (12, 13) have indicated moduli of foamed asphalt to be in the range of those for conventional bituminous bases made from similar aggregates. A detailed discussion of performance of foamed asphalt stabilized soil may be found in Shackel et al. (12). Basically, they found the repeated load triaxial responses of the foamed asphalt stabilized mixtures to be sensitive to the bitumen content, degree of aggregate saturation and penetration grade of binder. They also noted that: (1) there is a critical bitumen content at which the rate of strain accumulation is a minimum, (2) there is a critical saturation (50 to 70 percent) at which the resilient modulus is a maximum and (3) an increase in degrees of saturation at the commencement of repeated loading gives an increase in the strains and their rates of accumulation.

SUITABLE SOILS AND AGGREGATES

Only a modest amount of research has been conducted with foamed asphalt and soil-type aggregates. Initial reports indicate that the addition of foamed asphalt improves the physical properties of a wide range of engineering soils, from fine, non-plastic sands and sand loams through natural gravels to crushed stone products (14).

The presence of minus 200 mesh particles in soil apparently improves the ability of the foam to produce the essential uniform thin coatings on the finer fraction of the material. Dispersion of the binder alone is not enough to ensure the full benefits of the process (14).

Soils showing the greatest benefits from the addition of foamed asphalt are those showing dramatic loss of strength on exposure to water or water vapor, those lacking in natural cohesion and those which degrade in service by movement and abrasion at inter-partical contact points (14).

Through the use of properly designed and controlled equipment, asphalt cement in the form of a foam can coat fine-graded particles in a cold, damp condition. Coatings can be accomplished on soils varying from A-2-4 (0) to A-6 (9) (14). The moisture content of the soil is of great importance in the mixing process. The moisture content should be controlled between the amount necessary to assist in breaking up agglomerations of soil particles and permit the foamed asphalt to penetrate lumps of soil and optimum moisture content.

The cleaner sands may require the addition of some filler both to promote good mixing and to increase the "stiffness" of the mix. The filler in this situation will result in a stronger mix for a given grade of asphalt cement (14).

The shear strengths of a wide range of foamed asphalt stabilized sands were evaluated in the laboratory by Acott (15). The main properties influencing shear strength were particle shape and filler content. Low stabilities were obtained for particularly dirty and clean sands. A filler content of between 5 and 14 percent should be considered as a minimum grading requirement (15).

MIXTURE DESIGN

No criteria has been established for foamed asphalt mixture design. There does, however, exist some tentative test criteria in the literature by which to design foamed asphalt mixtures.

Bowering (10) developed a laboratory test system to adequately describe pavement materials incorporating foamed asphalt. The system was based on Hveem stabilization and aimed at clearly defining the effective range of binder content for significant improvement in material performance. It also provides information to allow assessment of the optimum binder content both for a particular material and for a given pavement service condition.

Bowering (10) selected six tests and modified them to suit materials produced by the addition of foamed asphalt to soils: (1) the "resistance value" test carried out before and after a 4-day soak at room temperature, (2) the relative stability test carried out before and after exposure to moisture vapor at 140°F for 3 days, (3) the unconfined compression test carried out before and after a 4-day soak at room temperature, (4) the cohesiometer test carried out before and after exposure to moisture vapor at 140°F, (5) the California permeability test and (6) the

California swell test.

Based on this work, Bowering suggested the following tentative limits on property values for satisfactory foamed asphalt mixtures of use immediately under thin seal treatments:

Modified R-value
  Minimum of 80 (cured specimens)
  Minimum of 80 percent retention after 4-day soak
Modified relative stability
  Minimum of 20 (cured specimens)
  Minimum of 15 after moisture-vapor susceptibility
Cohesion
  Minimum of 50 after moisture-vapor susceptibility
Free swell
  Maximum of 0.030 inches
Unconfined Compressive Strength
  Minimum of 100 psi (cured specimens)
  Minimum of 75 psi after 4-day soak.

Acott (15) found a good correlation between the resistance value and maximum vane shear strength. Based on this correlation he suggested that foamed asphalt mixtures should have a minimum R-value of 78 as prescribed by the Asphalt Institute for emulsion stabilized bases.

SUMMARY OF ADVANTAGES

Foamed asphalt may provide the following advantages:

1. It can be used to upgrade local aggregate of marginal quality.
2. Comparatively low bitumen contents are satisfactory.

3. It may provide a structural benefit to the pavement system thus reducing thickness of more expensive materials.
4. No aggregate heating is necessary.
5. No curing is required prior to compaction.
6. Because of rapid in situ mixing and compaction, construction time may be reduced.
7. Unsurfaced roads can be upgraded without base removal.
8. Foamed asphalt can be stockpiled and reworked.
9. Mixing and laying operations use standard equipment with only minor modifications.
10. Binder is standard asphalt cement with no added costs for hydrocarbon diluents or emulsifying water and chemicals or for transport of these fractions.

TEST PROGRAM

Laboratory experiments with paving mixtures containing foamed asphalt were conducted in accordance with Figures 1, 2 and 3. Figure 1 describes tests to determine the effects of asphalt cement content on the quality of mixtures and to aid in determining the optimum asphalt content. Figure 2 describes a more comprehensive program designed to determine comparative strength, stability, and water susceptibility, of foamed asphalt mixtures. Figure 3 depicts a series of flexural fatigue tests of 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 rather than 140°F.

A laboratory model asphalt foaming apparatus (Figure 4) was furnished by Continental Oil Company In Ponca City, Oklahoma, and used to produce the foamed asphalt throughout this study. The electrically powered device contains a three gallon 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 numerous trials were conducted using various aggregates, aggregate moisture contents, asphalt-water mixtures ratios and asphalt cement temperatures.

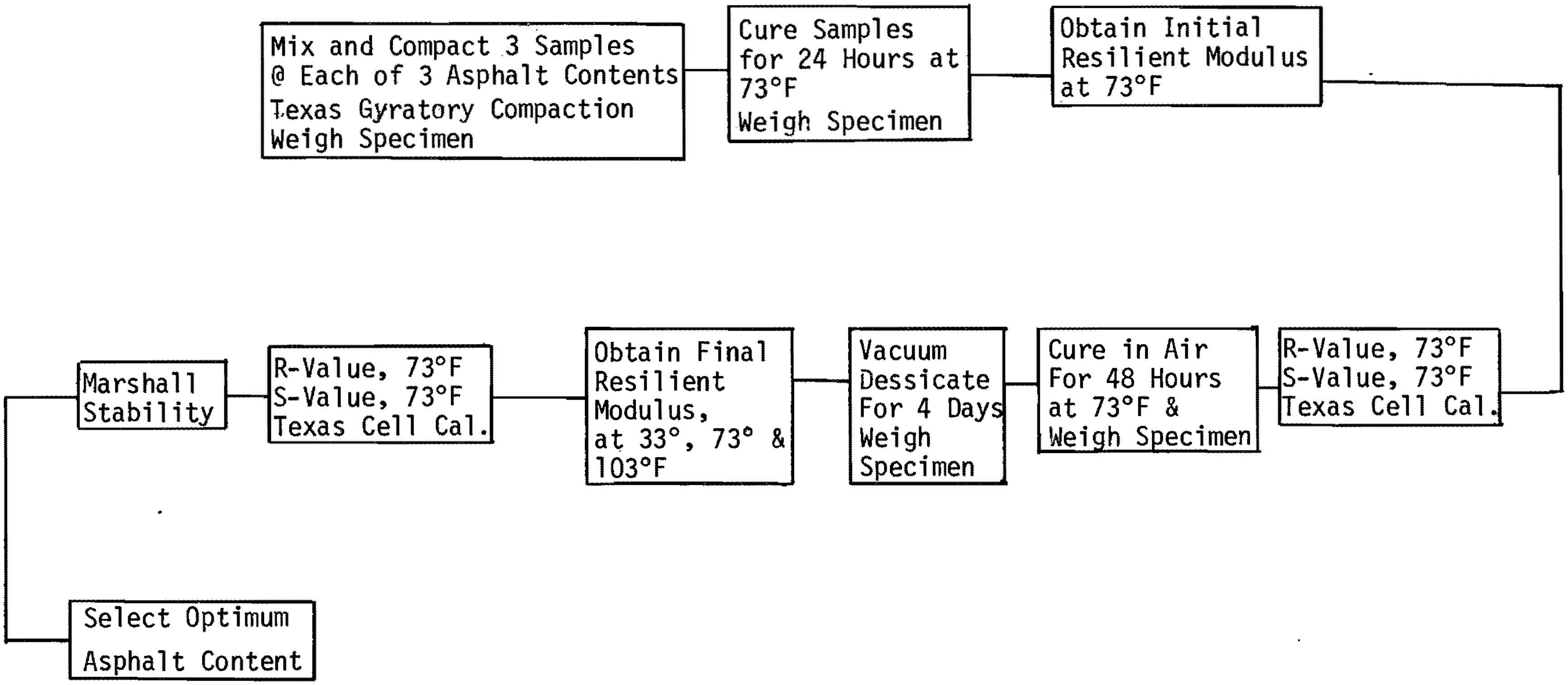


Figure 1. Test Program for Selection of Optimum Asphalt Content of Foamed Asphalt Test Specimens.

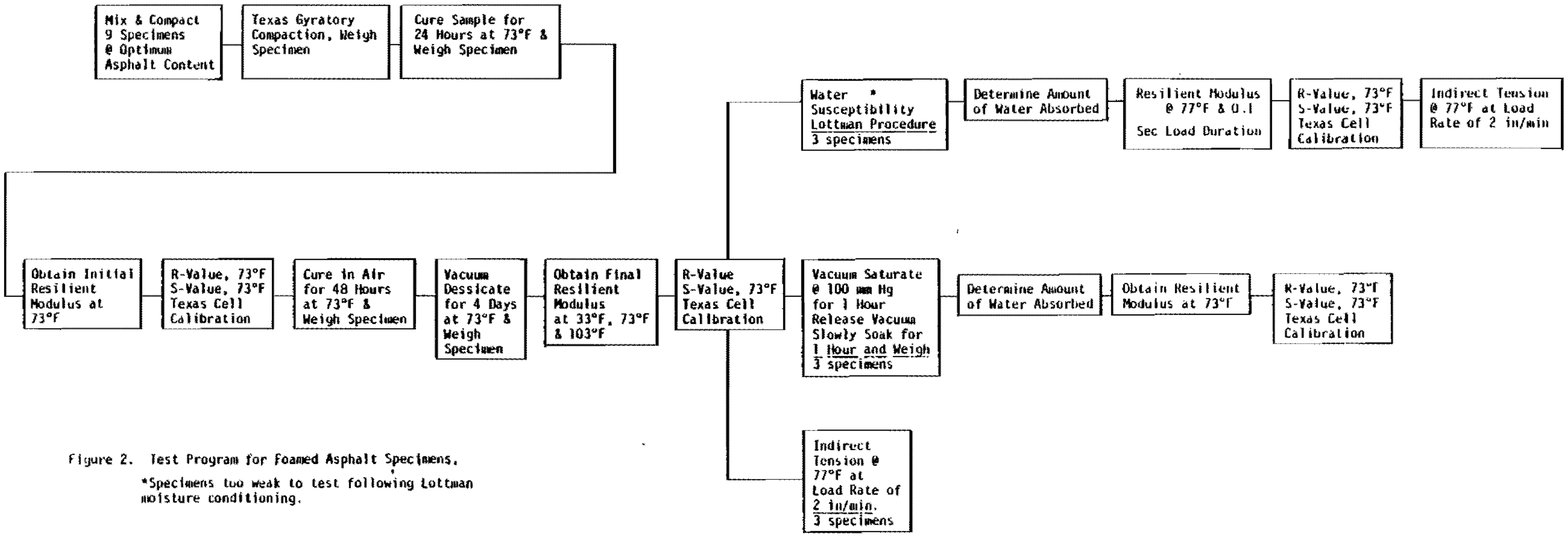


Figure 2. Test Program for Foamed Asphalt Specimens.

*Specimens too weak to test following Lottman moisture conditioning.

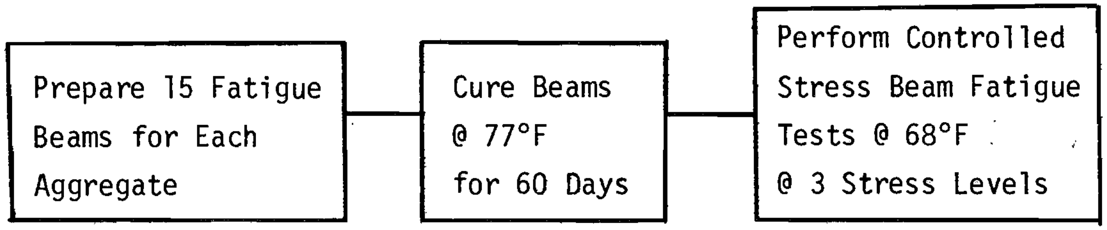


Figure 3. Foamed Asphalt Fatigue Test Program.

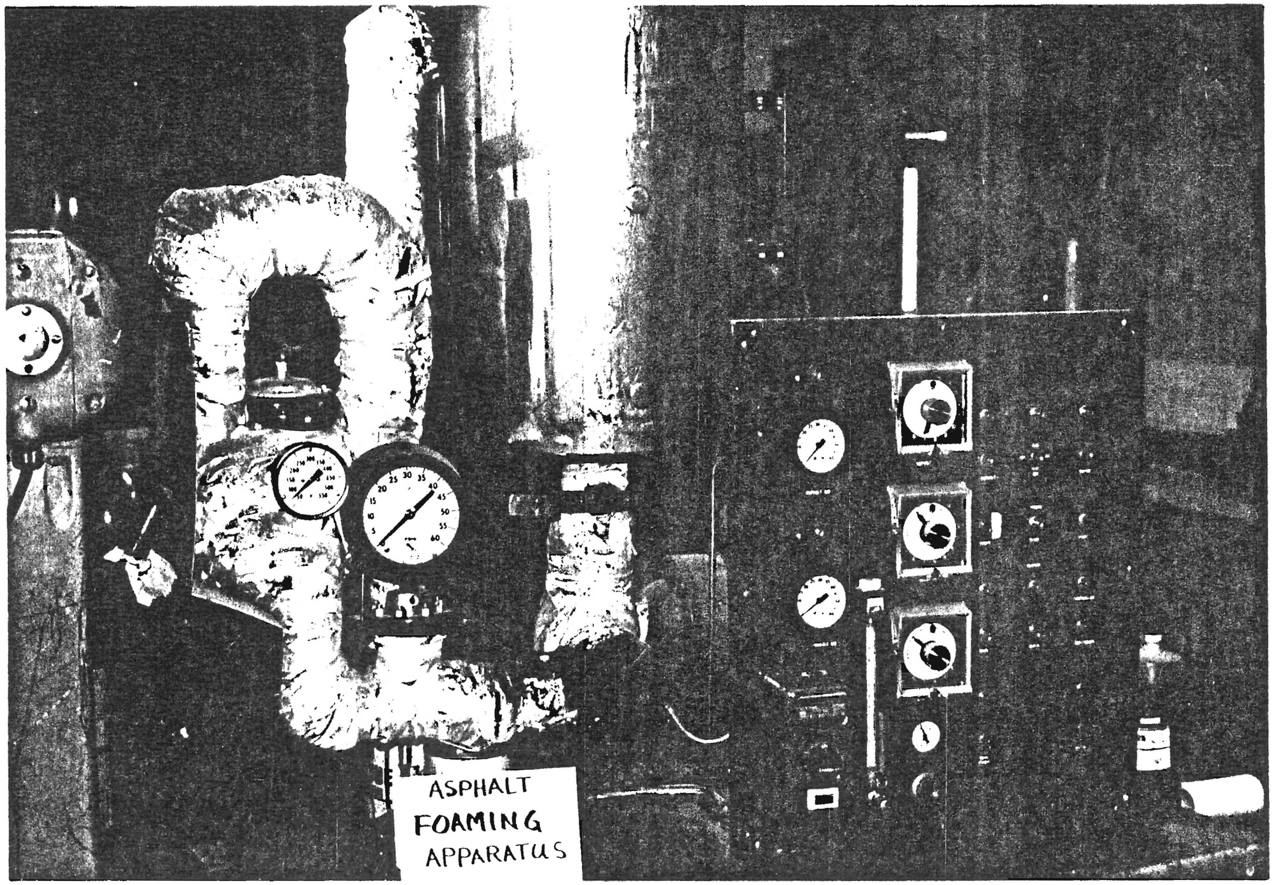


Figure 4. Laboratory Model Asphalt Foaming Apparatus.

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

Gradation plots of these aggregates are given in Figures B1 through B5, Appendix B.

ASPHALT

An AC-10 asphalt cement was obtained in 1976 from the American Petrofina refinery located near Mt. Pleasant, Texas. The properties of this viscosity graded asphalt cement is shown in Table B1. This asphalt is a laboratory standard asphalt at the Texas A&M University materials laboratory. According to comments from representatives of Continental Oil Company this asphalt does not foam as well as some asphalts. Foam volume and life was less than that exhibited by some asphalts. It was determined from American Petrofina representatives that this asphalt does not contain silicone, which would inhibit foaming. In order to improve foaming qualities a chemical additive, supplied by Conoco, was combined with all asphalt used to fabricate test specimens in this study.

FOAMING ADDITIVE

Identification of the chemical additive used to improve asphalt foam quality is proprietary and must remain unknown until the information is released by Continental Oil Company. Effects on asphalt foam quality produced by this additive is described in Appendix A.

TEST RESULTS AND DISCUSSION

GENERAL APPEARANCE OF MIXTURES

With foamed asphalt as a binder, the mixtures were not black like hot-mix asphalt concrete nor uniformly brown as an emulsion mixture. They were speckled. The asphalt cement appeared to form a semi-continuous matrix of small globules of asphalt with the finer aggregate. Photographs showing the appearance of the specimens are presented in Figures 5 and 6. The larger aggregate (plus No. 4 mesh) were hardly coated with the foamed asphalts.

DETERMINATION OF OPTIMUM ASPHALT CONTENT

The test program described 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 termed "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. Three specimens at each of three asphalt contents were mixed using foamed asphalt from the asphalt foaming apparatus and the dampened aggregates. After mixing, the mixtures were set aside for about 20 minutes and periodically stirred to allow evaporation of some of the moisture. Test specimens were compacted at room temperature (approximately 77°F), otherwise

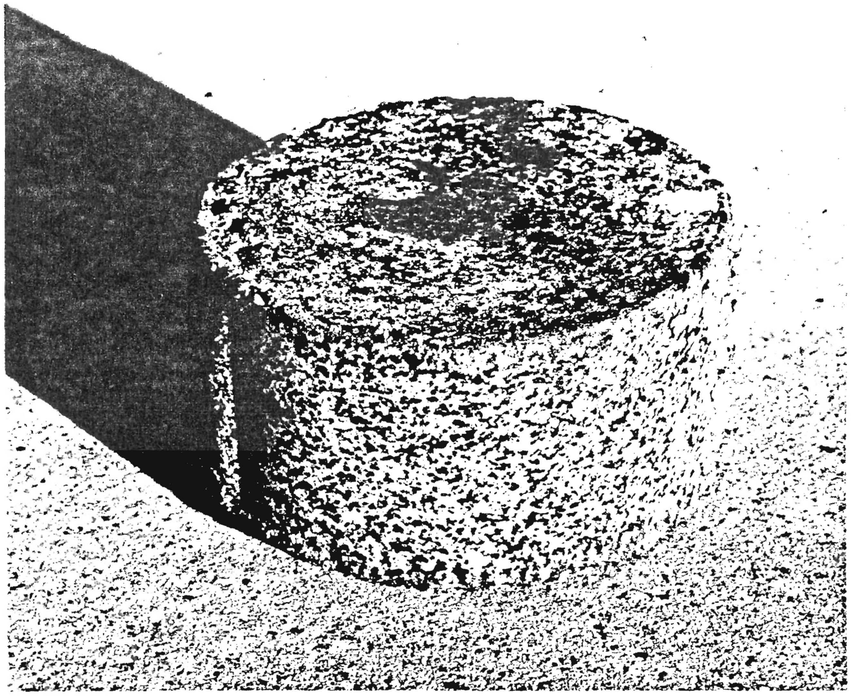


Figure 5. Marshall Specimen made with Sand and Foamed Asphalt

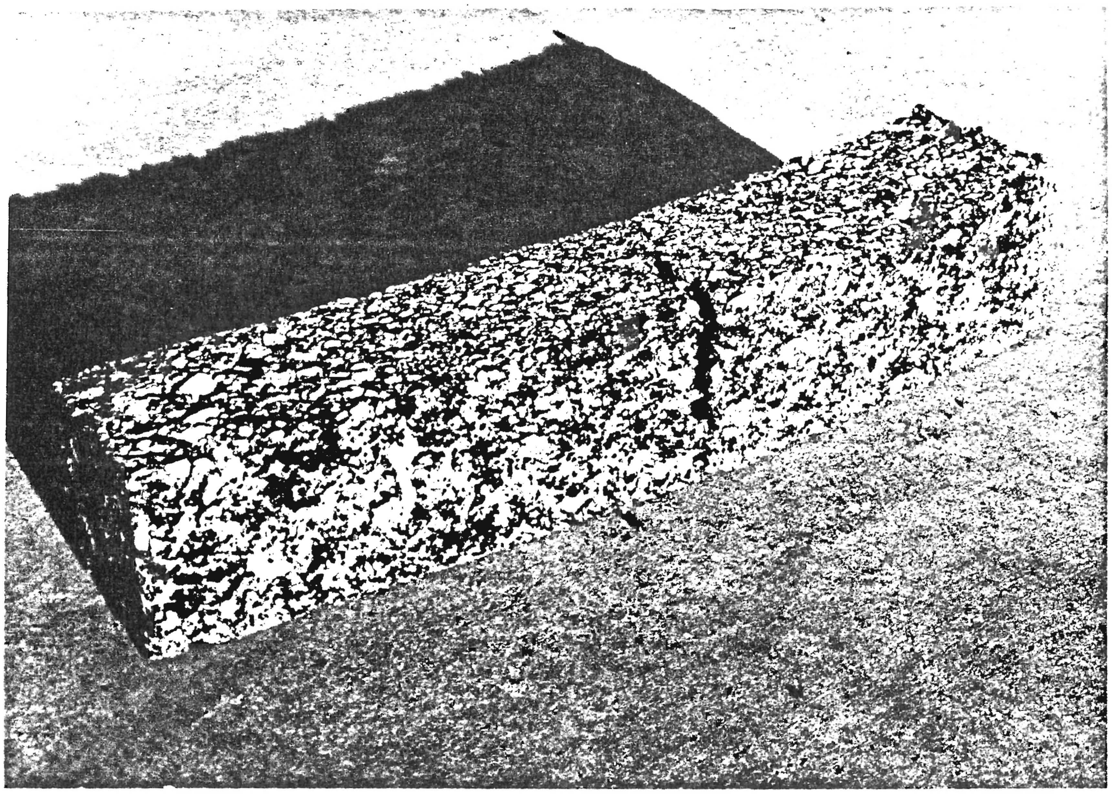


Figure 6. Fatigue Beam Specimen made with Laboratory Standard Aggregate and Foamed Asphalt

in accordance with Texas Department of Highways and Public Transportation test method TEX-206-F, Part II, "Motorized Gyratory-Shear Molding Press Operating Procedure".

The specimens were extracted from the mold and allowed to cure 24 hours at room temperature. Following initial testing, the specimens were allowed to cure an additional 48 hours then placed in a vacuum dessicator for 4 days. Upon removal from the dessicator the specimens were subjected to the final phase of testing as described in Figure 1.

Discussion of Results

A summary of results of the tests to determine optimum asphalt content is given on Table C1, Appendix C. The resilient modulus test of specimens aged for 24 hours was eliminated because the specimens were too fragile. Two specimens were broken while attempting this test. Weight of the specimens was monitored periodically and is recorded on Table C2.

Hveem Stability. Hveem stability was determined at 73°F for each specimen 24 hours after molding and again after the vacuum dessication treatment. Results are plotted on Figure 7 and 8. These tests were not conditioned at 140°F in order to eliminate any unrealistic heat effects or rapid drying of the test specimens. Hveem stability increased significantly upon drying by the vacuum dessicator. The blow sand from District 5 exhibited the lowest stability after drying. Based on Hveem stability after vacuum dessication, optimum asphalt content appears to be less than 3 percent for the sands from District 11 and 21 and greater than 7 percent for the sands from District

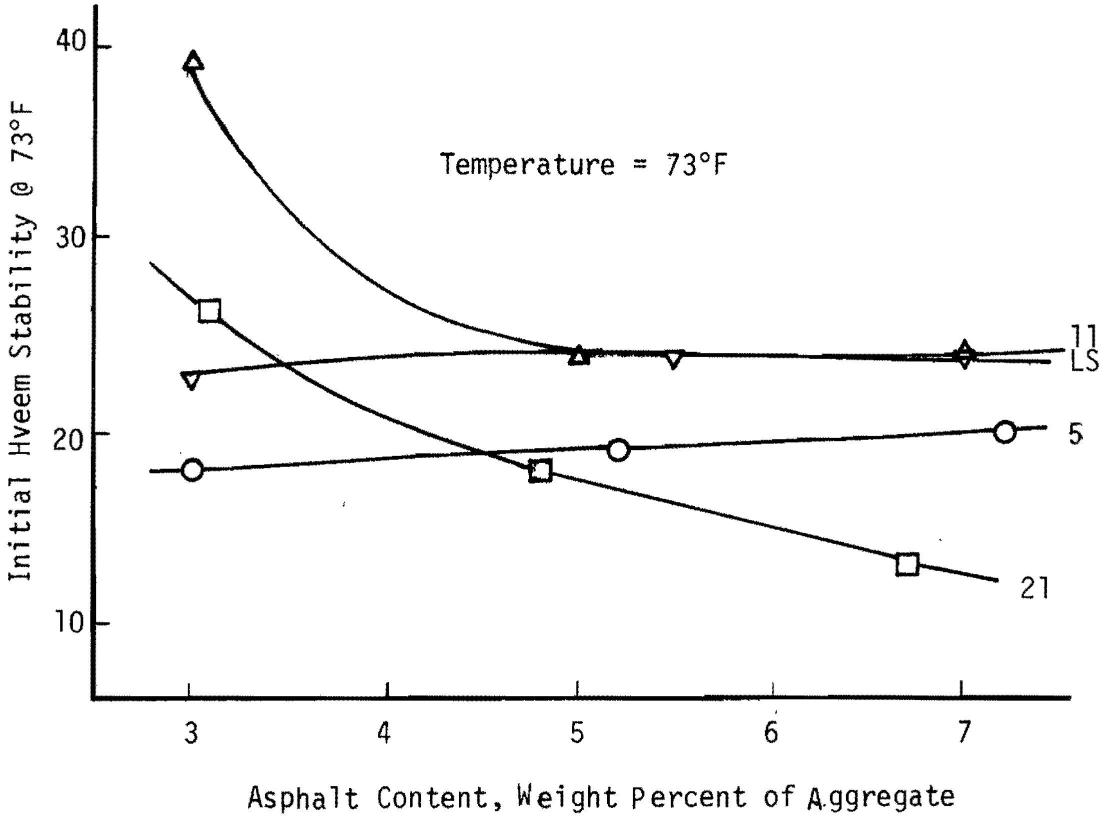


Figure 7. Hveem Stability versus Asphalt Content 24 Hours after Molding

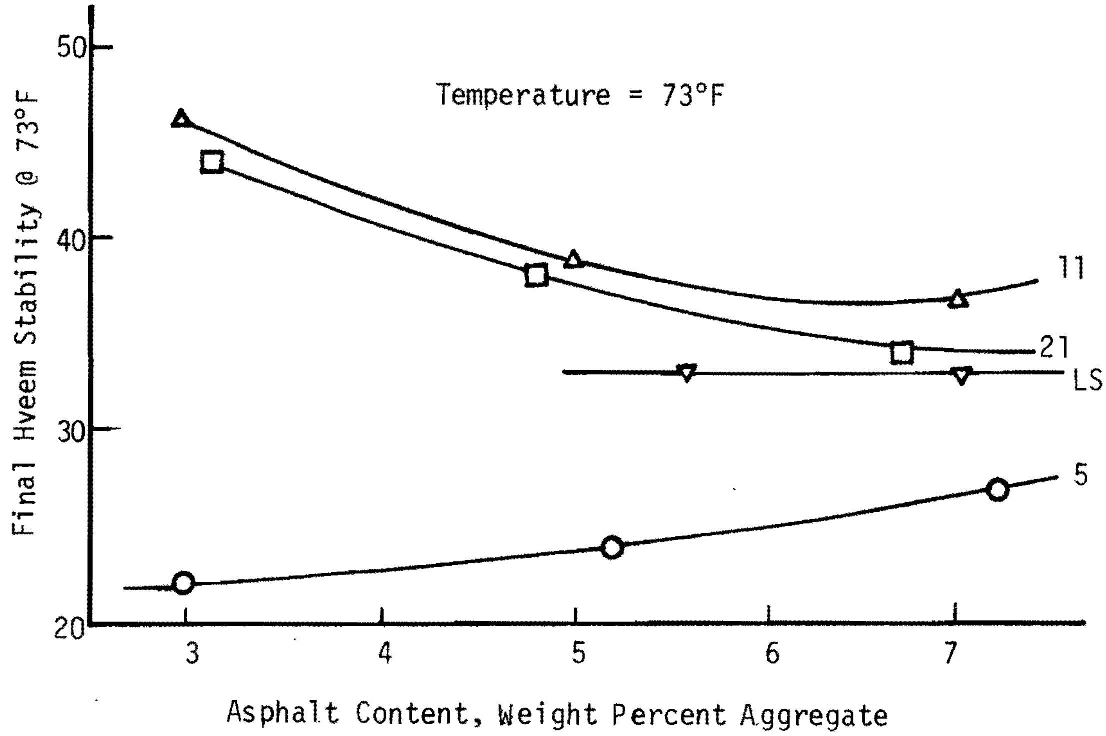


Figure 8. Hveem stability versus Asphalt Content after Vacuum Dessication

5. Asphalt content does not appreciably affect Hveem stability of the mixtures containing the laboratory standard aggregate.

Resilient Modulus. Resilient moduli at 33, 73, and 103°F were determined after vacuum dessication for specimens containing the various asphalt contents. These data are plotted in Figures 9, 10 and 11. Those specimens containing the laboratory standard aggregate exhibited the highest resilient modulus at 33°F but this trend is reversed at 73 and 103°F. This may relate to the selective coating of the finer aggregate in the gravel mix by the foamed asphalt. The poorly graded blow sand from District 5 exhibited the lowest resilient modulus of the three sands at all temperatures. Generally, resilient modulus at 33°F increases slightly with asphalt content and resilient modulus at 73 and 103°F decreases with increased asphalt content. However, based on resilient modulus, the optimum asphalt content for the sands, appears to be about 4 percent, whereas, optimum asphalt content for the laboratory standard aggregate may be greater than 7 percent.

Marshall Stability. The Marshall stability test was conducted at 73°F on specimens containing three different asphalt contents. Marshall stability and flow are plotted on Figures 12 and 13, respectively. The blow sand from District 5 exhibited comparatively low Marshall stability. This material has been shown to be very difficult to stabilize with asphalt. The sands from Districts 11 and 21 exhibited Marshall stabilities that compared well with that of the laboratory standard aggregate. Both of these materials have been stabilized with asphalts in the field and have given satisfactory performance. Based on Marshall stability, optimum asphalt contents appear to be near or

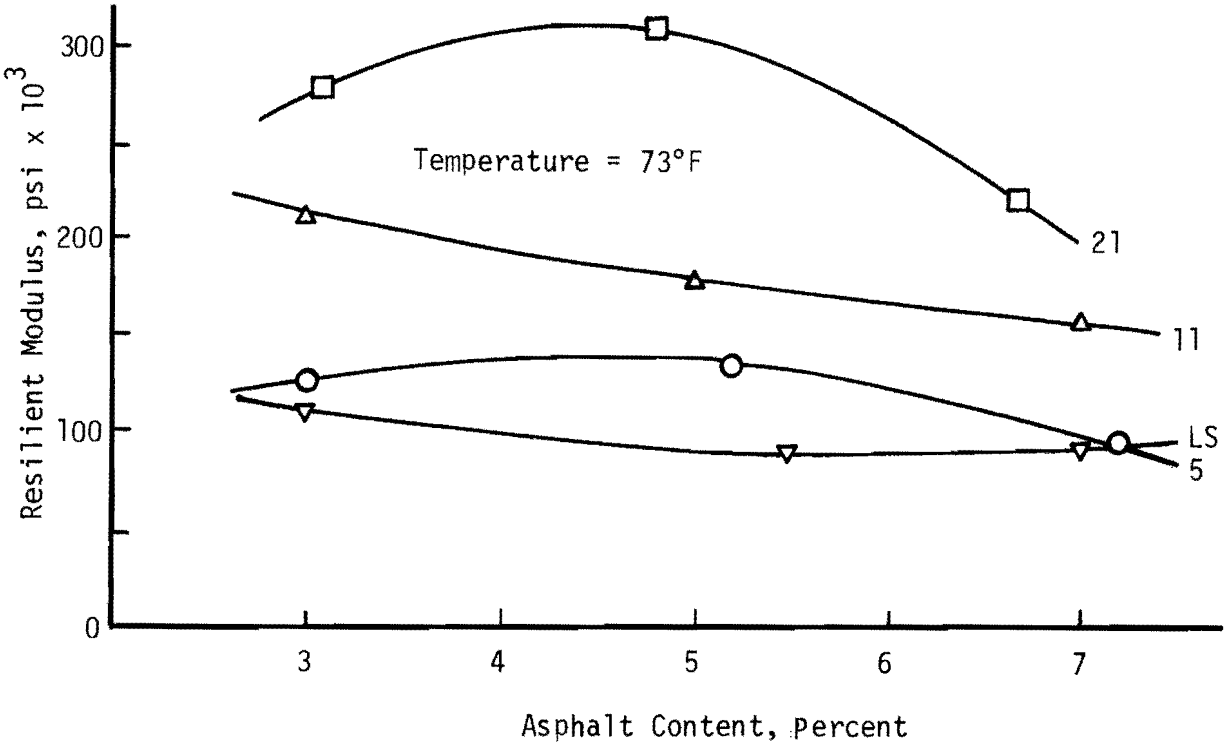


Figure 9. Relationship between Resilient Modulus at 73°F and Foamed Asphalt Content.

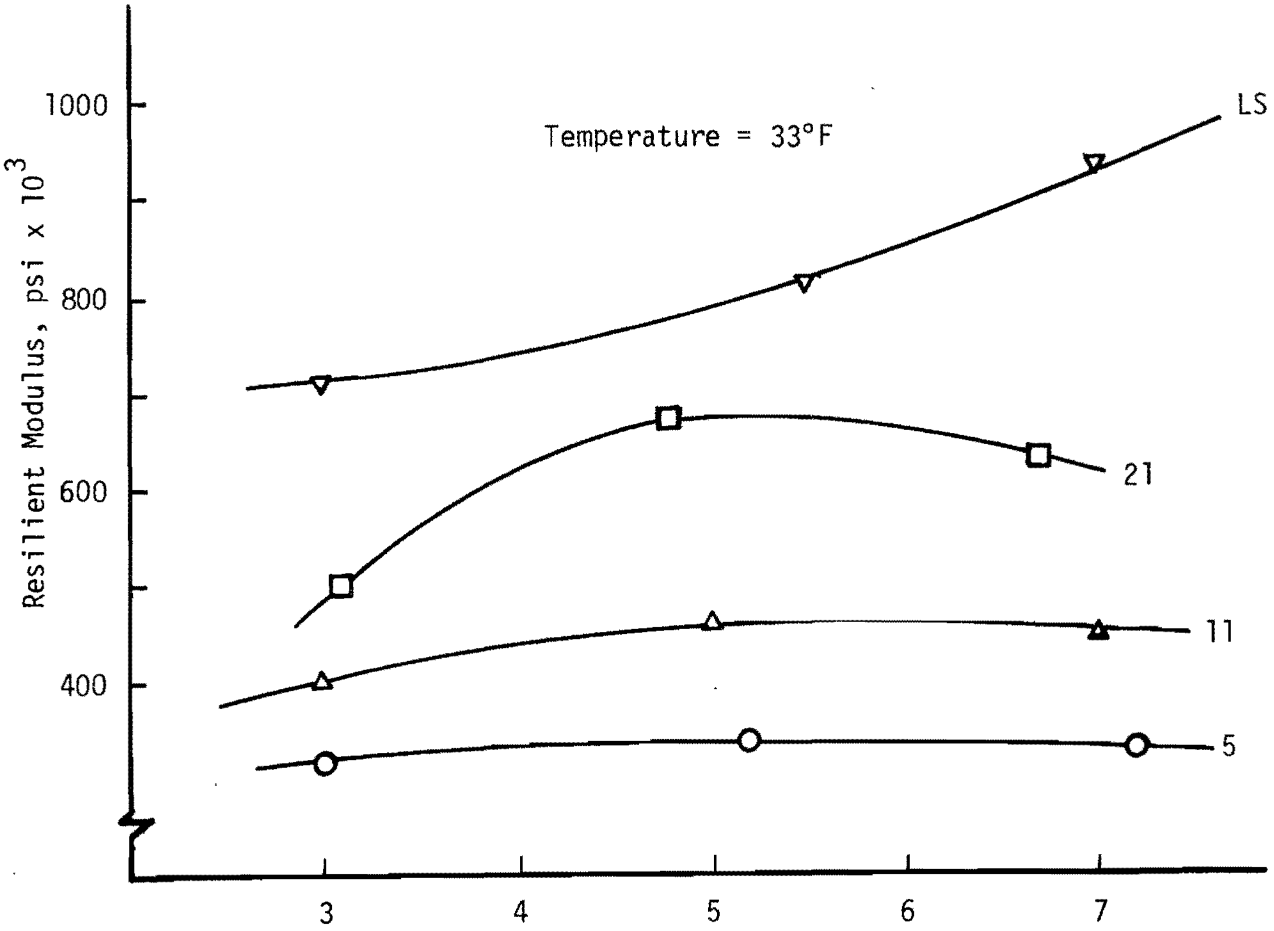


Figure 10. Relationship between Resilient Modulus at 33°F and Foamed Asphalt Content.

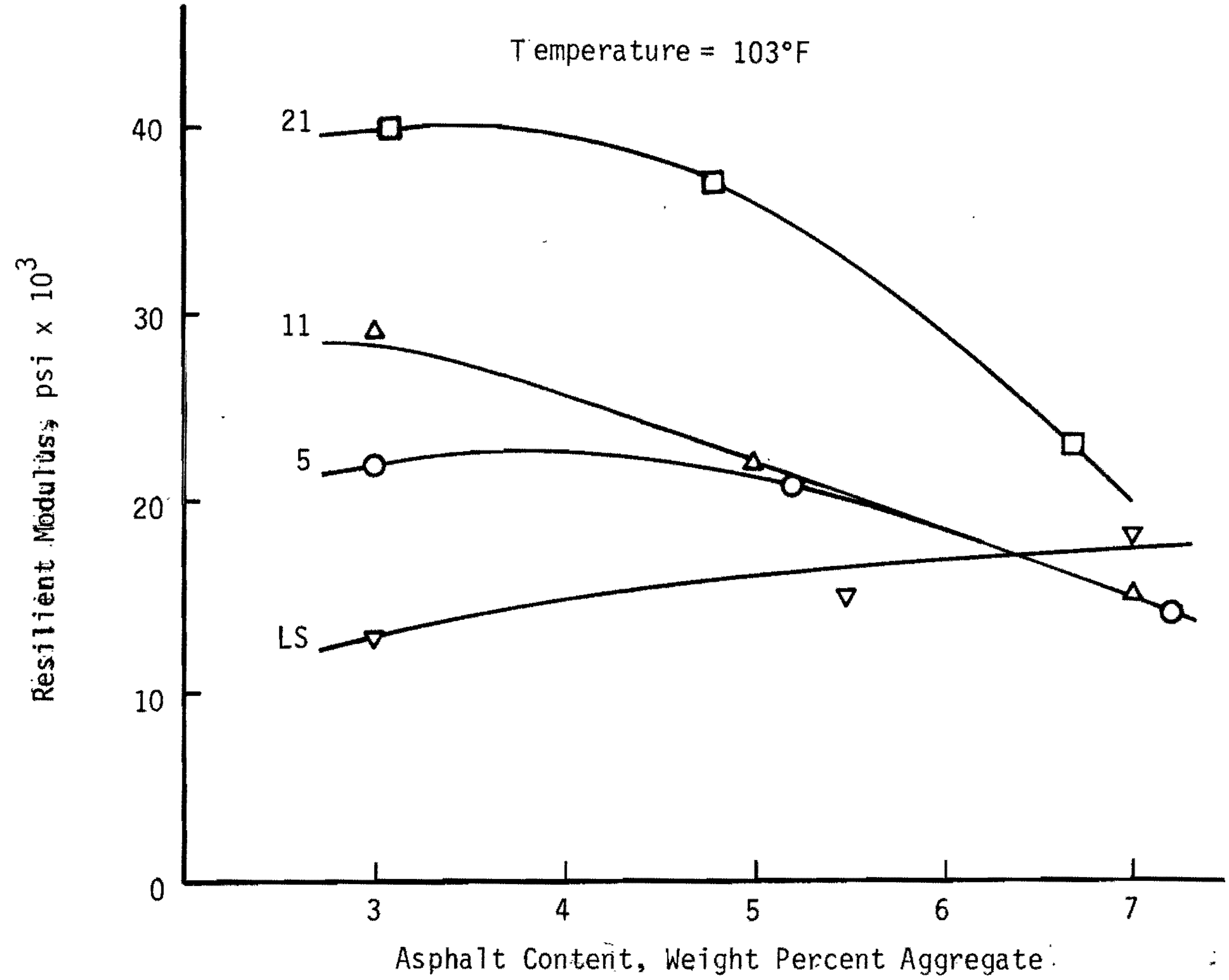
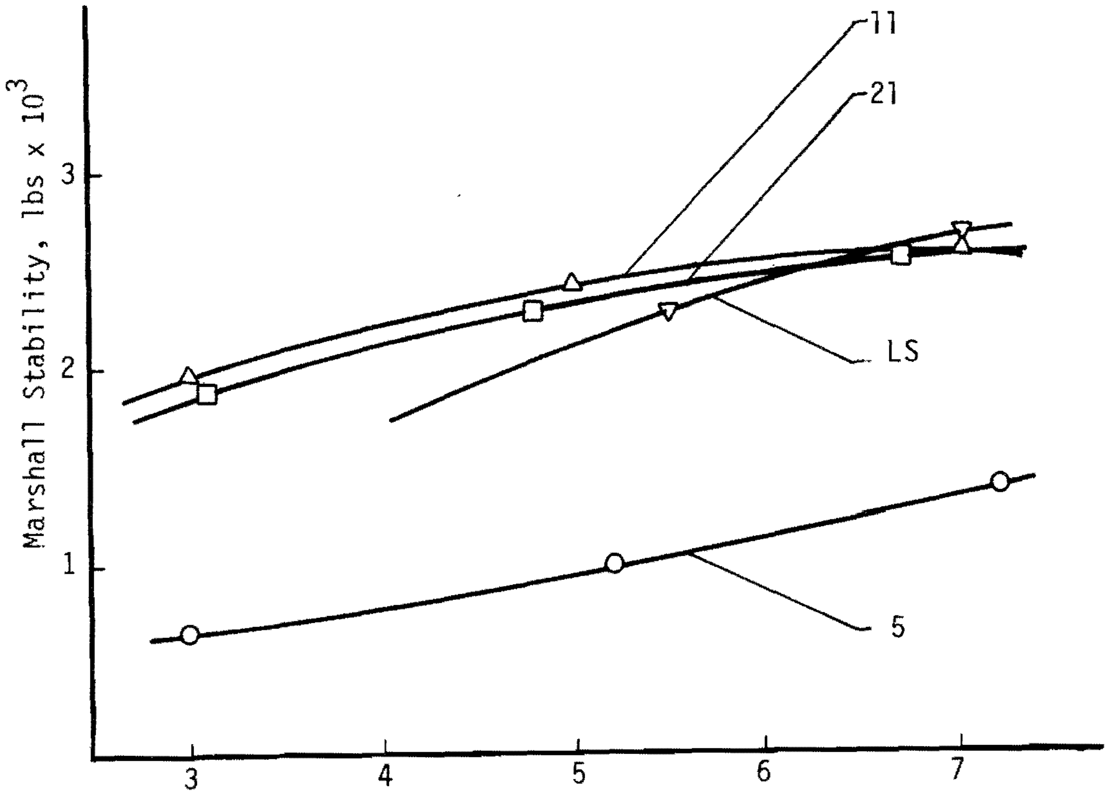


Figure 11. Relationship between Resilient Modulus at 103°F and Foamed Asphalt Content.



Asphalt Content, Weight Percent Aggregate

Figure 12. Marshall Stability at 73°F as a function of Foamed Asphalt Content.

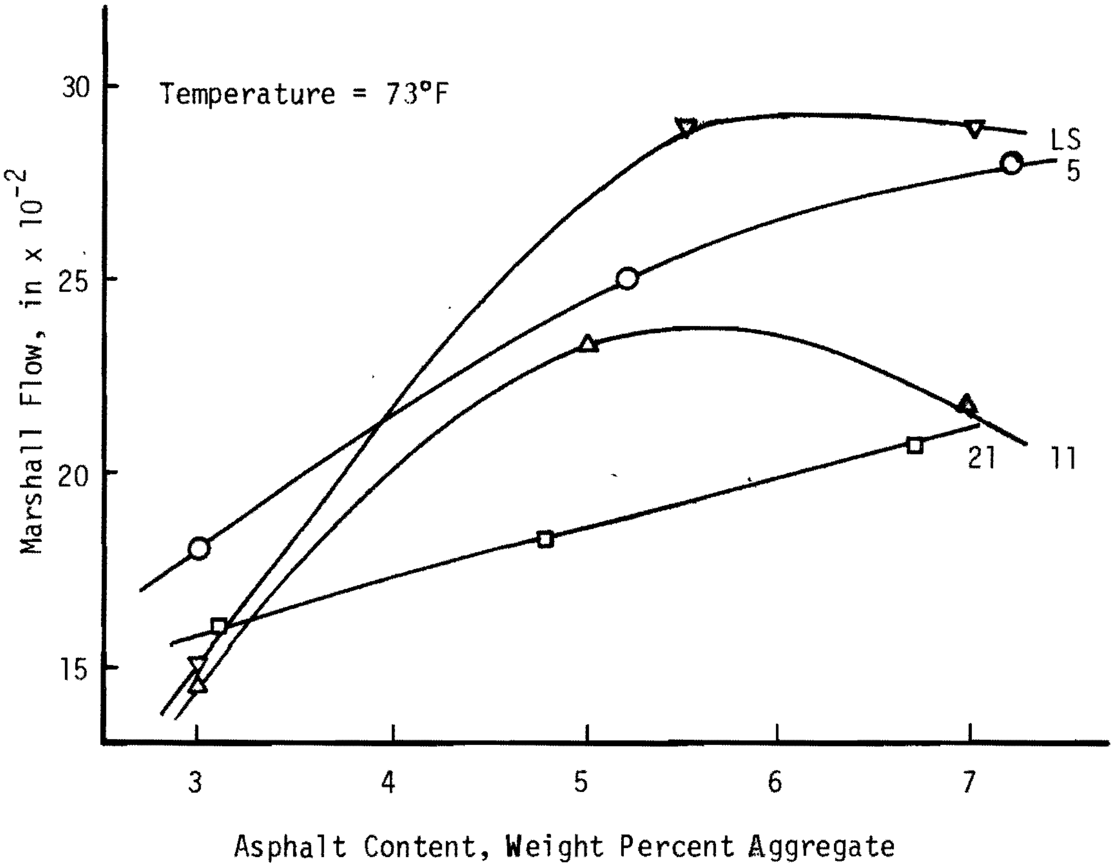


Figure 13. Marshall Flow as a Function of Foamed Asphalt Content.

somewhat greater than 7 percent for all the aggregates tested.

Optimum Asphalt Contents

The optimum foamed asphalt content selected for each aggregate was based on stiffness and stability test results, economics and engineering judgement. The design asphalt contents and moisture contents that were selected for each of the aggregates are shown in Table 1. These designs were used throughout the remainder of the test program.

TESTS AT OPTIMUM ASPHALT CONTENT

General

The laboratory test program in Figure 2 was developed specifically to compare strength, stability and water susceptibility of the foamed asphalt mixtures studied. As previously discussed the Hveem and Marshall stability tests are nonstandard in that they were performed at 73°F in lieu of 140°F. This was due to the instability of the foamed asphalt-sand mixtures at the higher temperatures. As such, the non-standard tests are used only for comparative purposes, between and among mixtures evaluated in this study. However, it should be noted that several agencies do currently accept stabilities measured at these low temperatures as realistic for base materials

Data from this portion of the study are summarized in Tables C3 and C4, Appendix C.

Hveem Stabilities and R-Values

The Hveem stabilities and resistance of "R-Values" of the mixtures tested are summarized in Figures 14 and 15. It is apparent that the

Table 1. Paving Mixture Designs for Foamed Asphalt Study.

Aggregate	Asphalt Content, Percent By Dry Weight of Aggregate	Moisture Content, Percent By Dry Weight of Aggregate
Blow Sand District 5	5.2	8
Field Sand District 11	6.0	8
Beach Sand District 16	7.0	8
Off-Beach Sand District 21	5.2	8
Laboratory Standard District 17	4.5	5
Blow Sand (Dist 5) + 10% River Silt(-#200)*	5.0	8
Beach Sand (Dist 16) + 10% River Silt(-#200)*	7.0	8

*These mixtures will be discussed later.

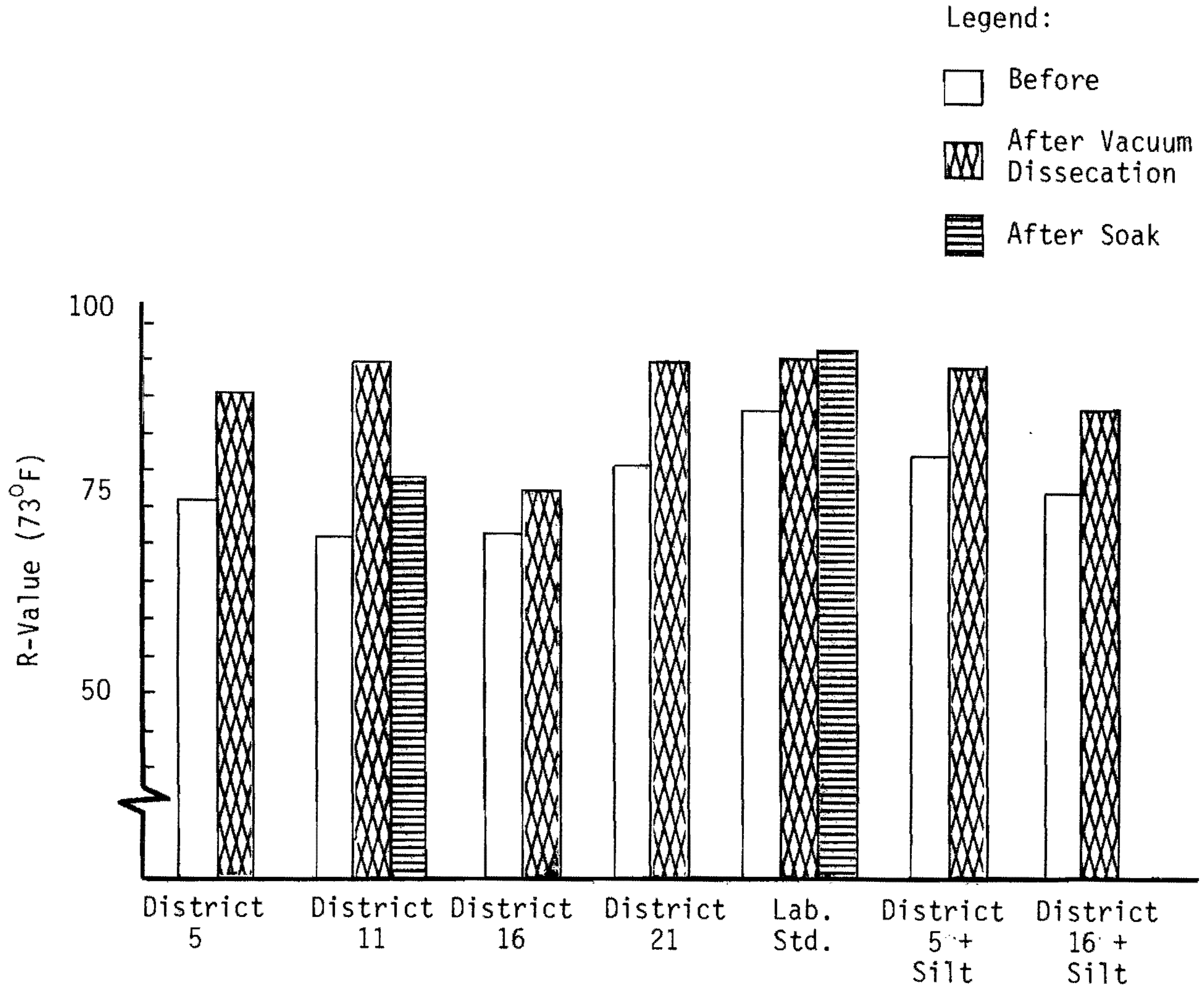


Figure 14. Resistance Value before and after Vacuum Dessication and 7-day Soak

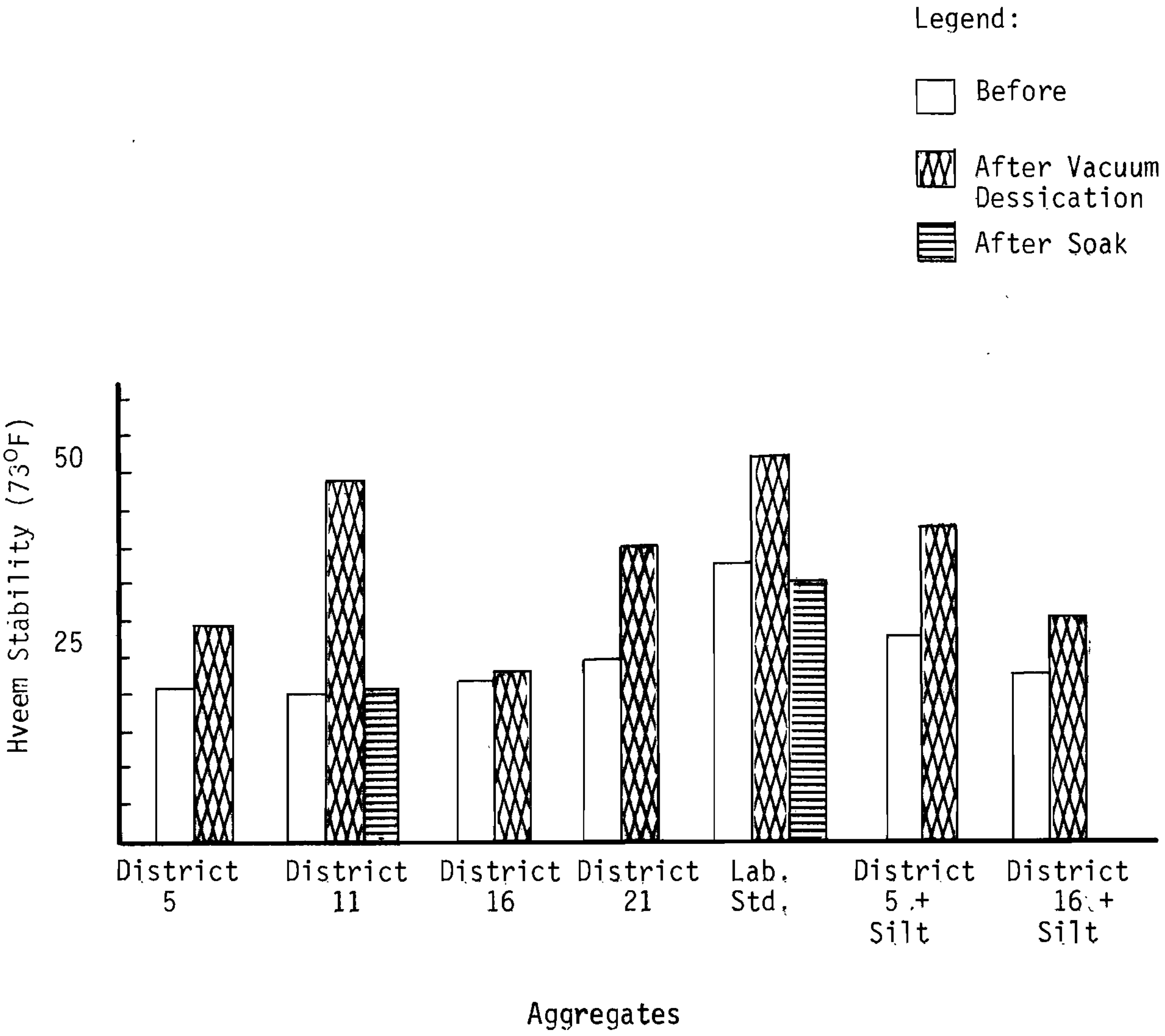


Figure 15. Hveem Stability before and after Vacuum Dessication and 7-day Soak

stabilities increase significantly for each mixture following the 4-day vacuum dissication period which represents a total curing period of 7 days. This illustrates the criticality of moisture reduction by proper curing in the strength gain process.

The respective increases in Hveem stabilities and resistance values are recorded in Table 2.

The Hveem stabilities measured at 73°F cannot be compared to standardized criteria. However, one can use these values (after full curing) to evaluate the relative stabilities of the mixtures studied. Table 3 summarizes this comparative evaluation together with a comparative evaluation of R-Values. Also recorded in Table 3 are the mixtures which, based on their fully cured R-Values, possess sufficient stability for use as base courses according to the Asphalt Institute criteria (7) for emulsion treated bases.

Only the laboratory standard aggregate and the well graded sand from District 11 are suitable for base courses based on after vacuum saturation R-Values. However, all mixtures, except the District 16 mixture, have relatively high R-Values prior to soak. This indicates an inability of the foamed asphalt used in this test program to properly water-proof and thus stabilize certain of these aggregates.

Resilient Moduli

The resilient moduli data will be discussed from a structural view point in the following section. Figure 16 summarizes the resilient modulus, M_R, data as obtained from the Schmidt diametral resilient modulus testing device (17) over a range of temperatures. Figure 16

Table 2. Percentage Stability Increases Due to Vacuum Dessication (Full Curing).

Aggregate	Percent Increase in Hveem Stability	Percent Increase in R-Value
District 5	43	24
District 11	145	42
District 16	5	7
District 21	64	21
Lab. Standard	39	9
Dist. 5 + Silt	54	19
Dist. 16 + Silt	35	18

Table 3. Evaluation of Hveem Stabilities and R-Values @ 73°F After Full Curing and Moisture Treatment

Aggregate	Hveem Stability	R-Value	Acceptable Before Soak	Acceptable** After Soak
District 5	30 (D)*	88 (D)	Yes	No
District 5 + Silt	43 (D)	92 (D)	Yes	No
District 11	49 (20)	94 (78)	Yes	Yes
District 16	23 (D)	74 (D)	No	No
District 16 + Silt	31 (D)	86 (D)	Yes	No
District 21	41 (D)	93 (D)	Yes	No
Lab. Standard	53 (35)	94 (95)	Yes	Yes

*Value after Soak (D = Disintegrated)

**Note the R-Value criterion is 78 for a base course after vacuum saturation.

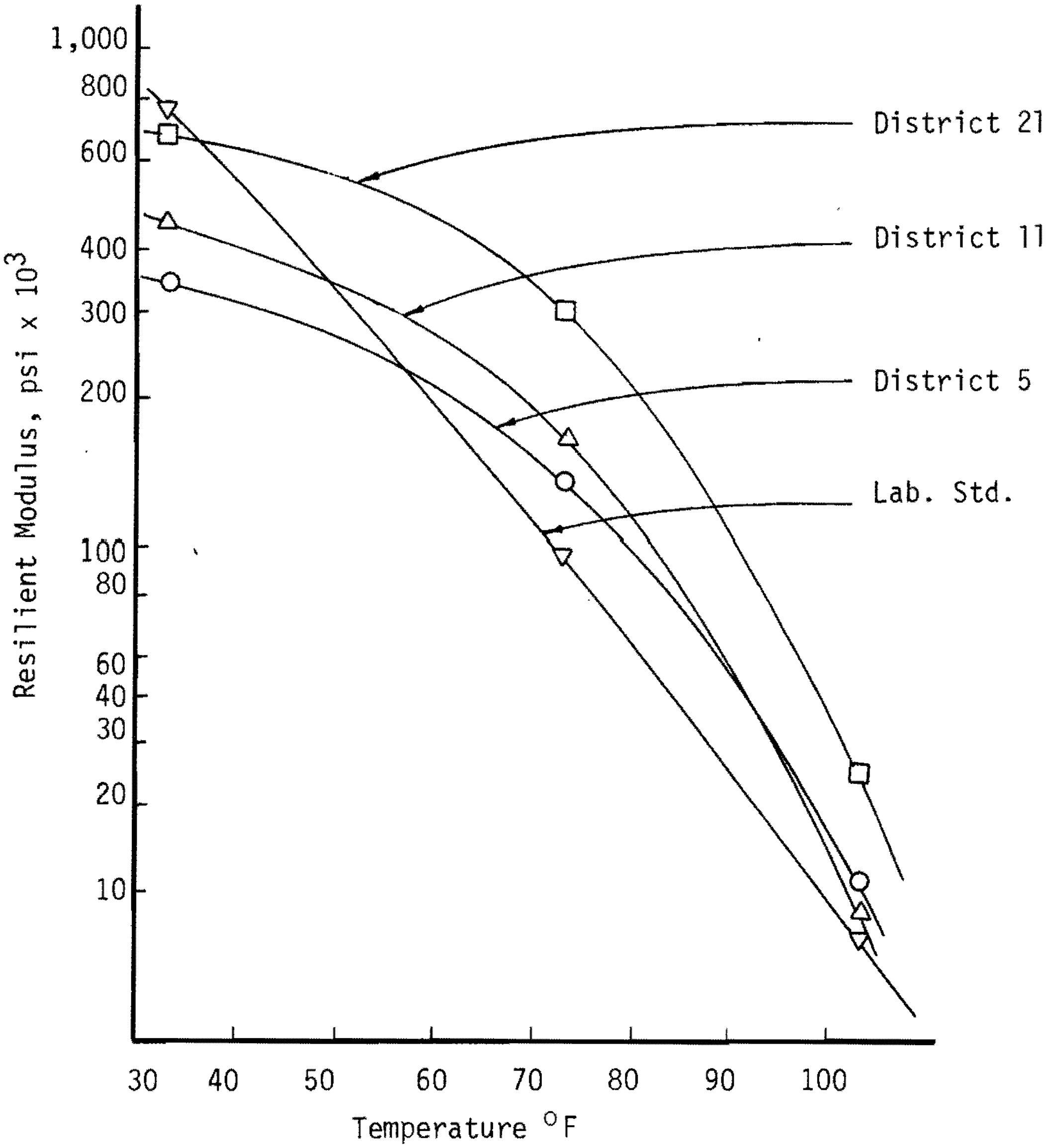


Figure 16. Resilient Modulus as a Function of Temperature for the Foamed Asphalt Specimens.

indicates that stiffer mixtures are obtained with the well-graded sands of Districts 11 and 21. This is not surprising as the asphalt appeared to be disersed more uniformly and completely in the well-graded material. The laboratory standard aggregate on the other hand was erratically coated. The asphalt was concentrated in the fines but left the No. 4 sieve size and larger material virtually uncoated. Table C1 (Appendix C) indicates that asphalt content is not a critical factor regarding the resilient modulus of most of the mixtures studied. Perhaps this is due to the fact that these specimens are not totally "bound" by asphalt and that additional asphalt tends to concentrate still more in the fine aggregate and does not coat additional aggregate particles.

Published data (9) indicate that the temperature susceptibility of foamed asphalt specimens is much less than for hot mixed specimens. However, this was not evident for the materials studied here. See Figure 17. Temperature susceptibility appears to be comparable or perhaps slightly greater than that for hot mix specimens at the higher temperatures (greater than 70°F). However, at lower temperatures the temperature susceptibility of foamed asphalt does appear to be less.

Splitting Tensile Testing

The splitting tensile test has been adopted by many researchers as the best method to evaluate the tensile properties of stabilized pavement materials (18, 19). However, it is quite difficult to evaluate the results of such tests on the foamed asphalt stabilized sands evaluated in this study. This is because no criteria for evaluating such materials has been established.

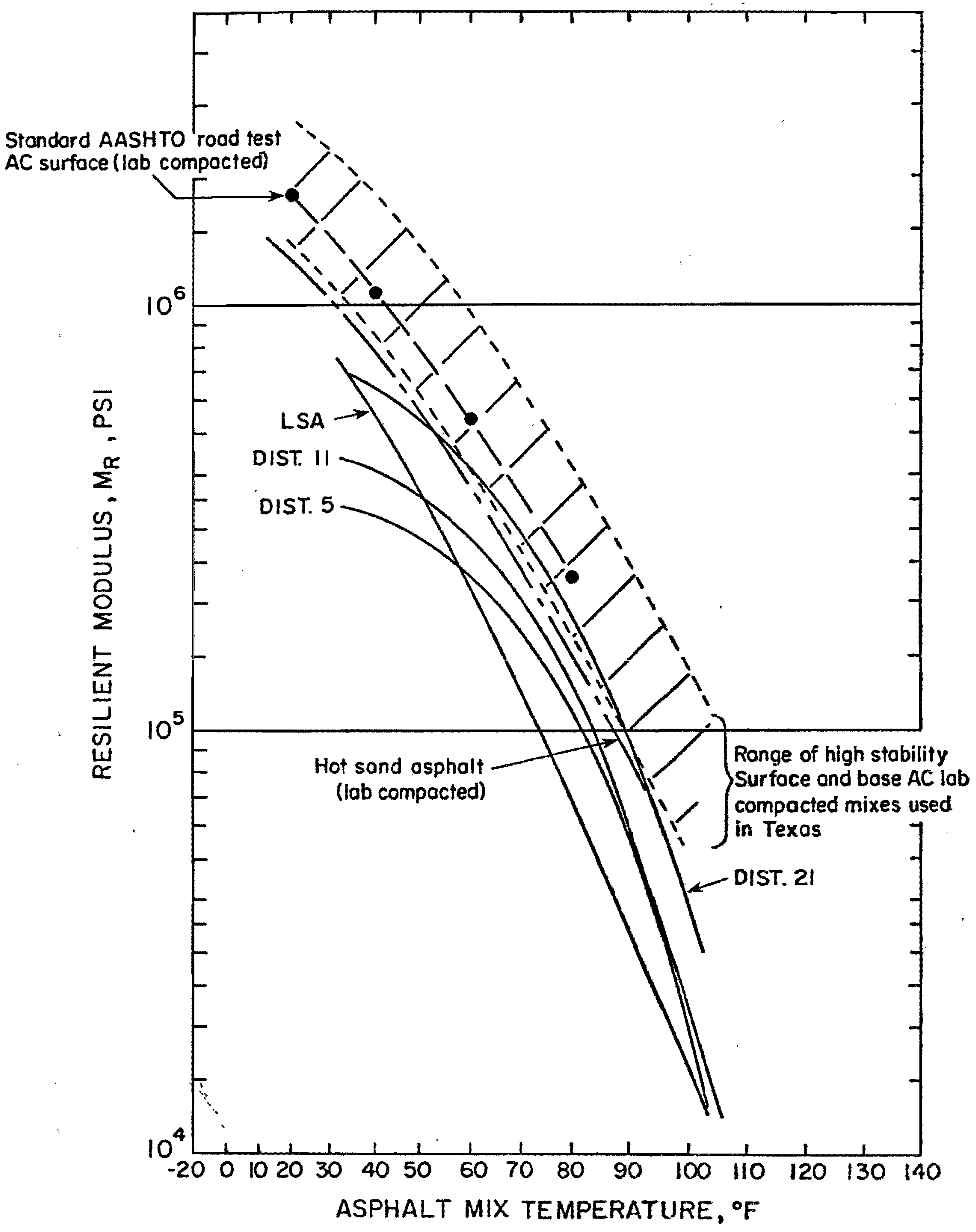


Figure 17. M_R vs. Temperature Relationships for Foamed Asphalt Mixtures.

Figure 18 provides a comparison of the tensile properties of the foamed asphalt mixtures tested, based on the following properties: 1) tensile strength, 2) tensile strain and 3) secant elastic modulus. This figure illustrates the benefit of the 10 percent silt added to the sands from Districts 5 and 16.

Figure 19 illustrates tensile strength of the foamed asphalt laboratory molded specimens and compares them to conventional asphalt concrete field core specimens. The shaded irregular polygon represents a grouping of data points representing splitting tensile properties from over 200 specimens representing 16 successfully performing Texas pavements. These pavements represent a wide geographical cross-section of Texas. The loci of ultimate tensile stress and tensile strain for the foamed asphalt specimens are identified by the district number from which the aggregates were obtained. The dashed lines originating from zero present the secant modulus of the specimens at failure. All tests were performed at a loading rate of 2 inches per minute and at a temperature of 73°F.

The foamed specimens exhibited comparatively low ultimate tensile strengths and failed at very low tensile strains indicating their instability for use in pavement layers subjected to high tensile stresses or strain.

Research by Thompson (19) in lime stabilized soils indicated the splitting tensile strengths to be in the range of 65 to 200 psi for fully cured specimens. These values are well in excess of those exhibited by the foamed asphalt specimens. On the other hand, Tulloch, et al. (20) indicated splitting tensile strengths from 20 to 90 psi to be common

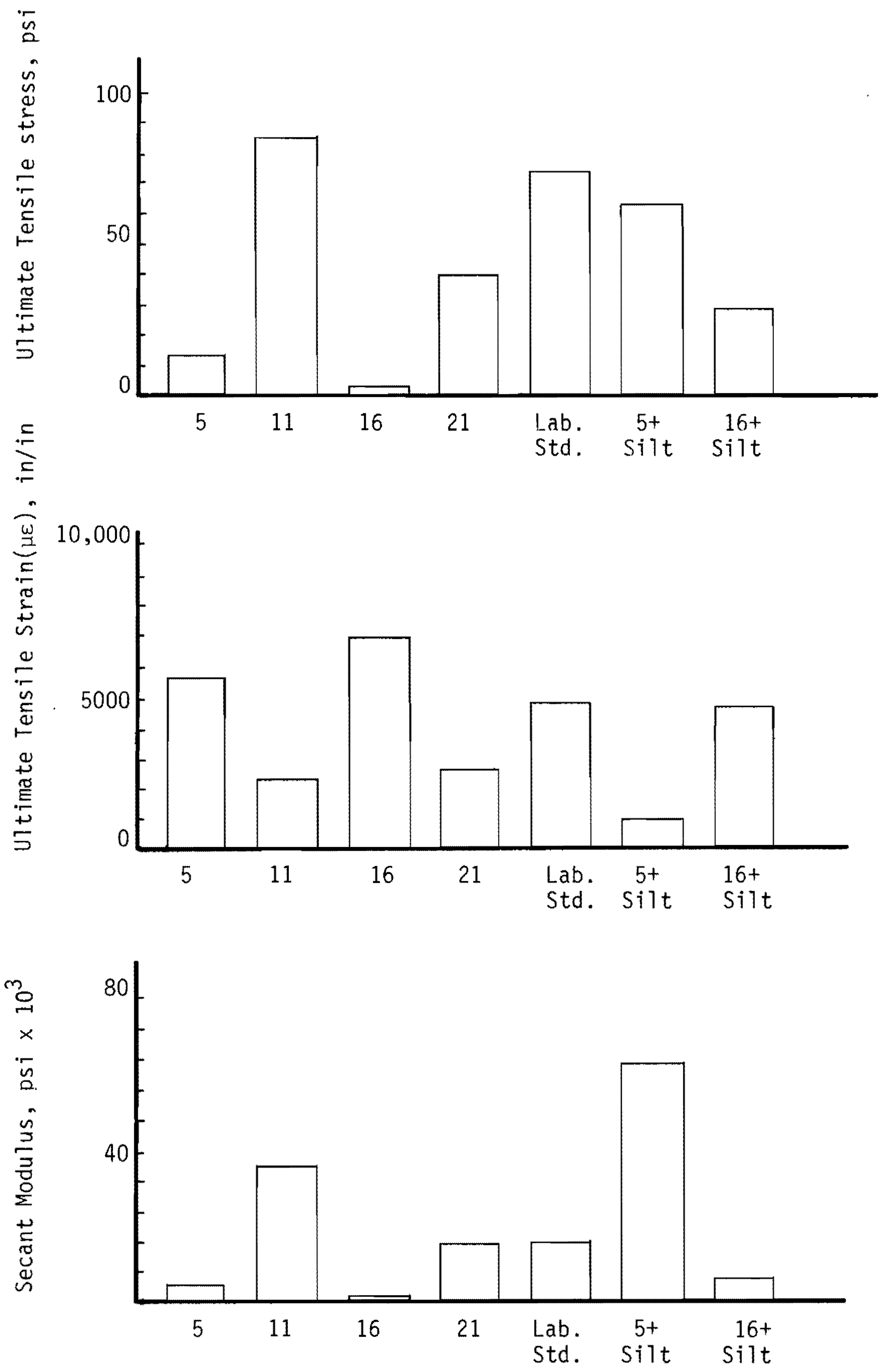


Figure 18. Data from Splitting Tensile Test

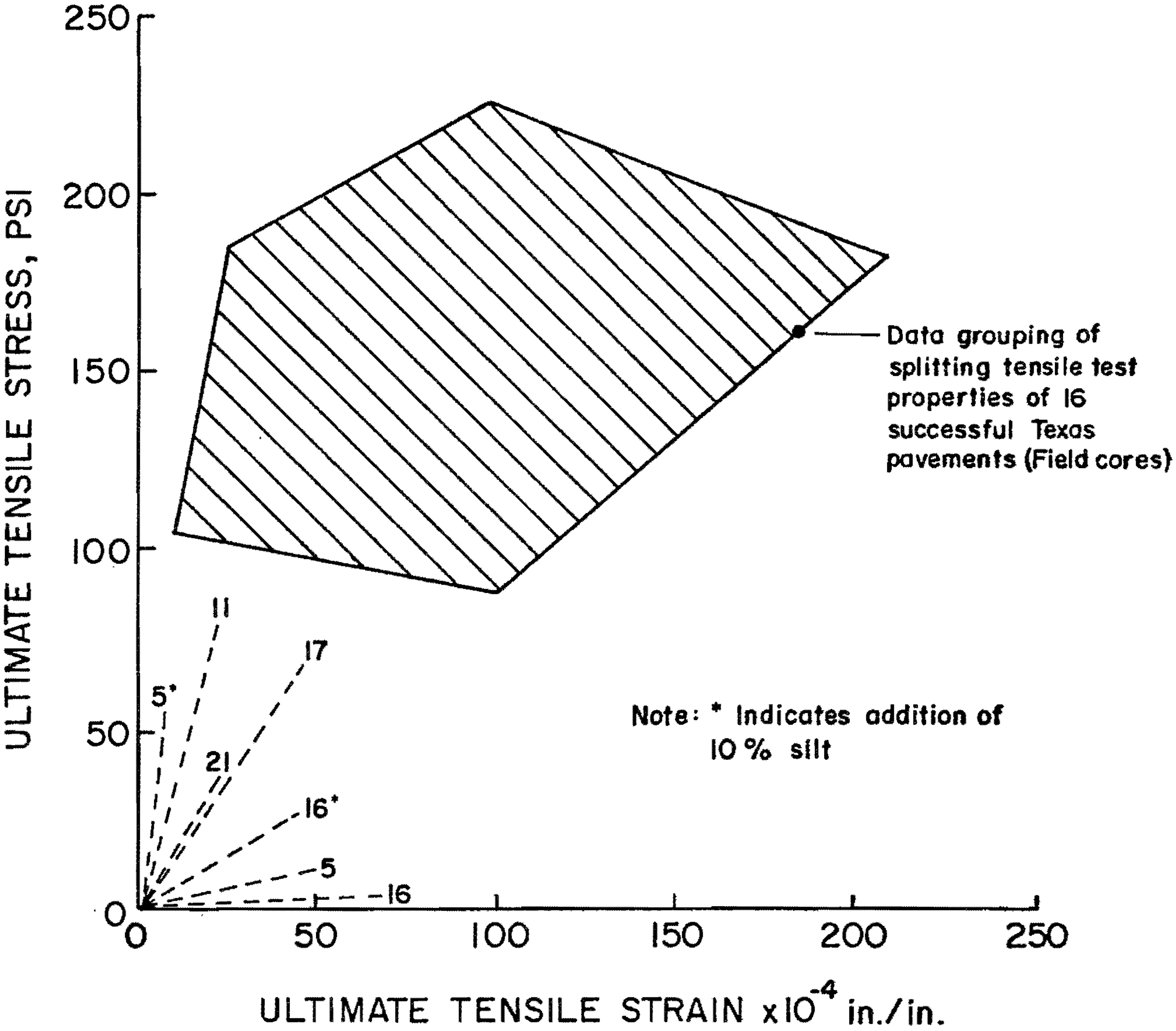


Figure 19. Comparison of Splitting Tension Data of Foamed Asphalt Specimens with Splitting Tension Data of 16 Successfully Performing Texas Asphalt Concrete Pavements.

for lime stabilized soils. In this case, the foamed asphalt mixtures from Districts 11 and 21 may have tensile properties comparable to some lime stabilized soils.

STRUCTURAL EVALUATION OF FOAMED ASPHALT MIXTURES

Foamed asphalt mixtures were evaluated in terms of their ability to perform as part of a structural pavement system. This structural evaluation is based on the results of:

1. Diametral resilient modulus versus temperature,
2. Beam flexural fatigue and
3. Hveem stability.

Resilient modulus data are necessary in order to characterize these materials in a layered elastic model of the pavement system. The BISAR multi-layered elastic computer program and the Chevron stress sensitive layered elastic program 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 by ascertaining 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 was used for this purpose. Foamed asphalt mixtures were tested at 32°F, 73°F and 104°F. This range in temperature should represent the range developed in most asphalt bases in Texas. Although pavement temperatrues in uppermost asphalt concrete layers may approach 140°F, resilient modulus testing using the Schmidt device at these extremely high temperatures is impractical. The duration rate of loading in the diametral resilient modulus test is 0.10 seconds which is representative of the duration of moving wheel loads.

With the resilient modulus known at the conditions of loading and temperatures expected in the field, the layered elastic pavement model becomes a valuable analytical tool, in that mechanistic responses may be calculated and analyzed.

POTENTIAL AS BASE MATERIAL

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, $\partial\sigma_z/\partial z$, increases negatively in magnitude. 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. Thus, shear stresses build-up through the reinforcing layer with increase in E_1/E_2 in accordance with the equation of stress equilibrium:

$$\frac{\partial\sigma_z}{\partial z} + \frac{\partial\tau_{rz}}{\partial r} + \frac{\tau_{rz}}{r} = 0 \qquad (1)$$

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 may 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 as an asphalt stabilized base or as a full depth asphalt stabilized pavement is acceptable fatigue life characteristics.

The following paragraphs discuss the potential of foamed asphalt as a structural base course or a structural full depth layer based on these three items:

1. Distribution of vertical stresses,
2. Resistance to shearing failure and
3. Fatigue life characteristics.

DISTRIBUTION OF VERTICAL STRESSES

The relative ability of the foamed asphalts to distribute vertical stresses and thus reduce critical subgrade strains or subgrade deflections can be estimated from the M_R vs. temperature curves. However, to more vividly illustrate this ability, the foamed asphalt was compared to the high quality asphalt stabilized base materials used at the AASHTO Road Test. The comparison was made by two methods. First, AASHTO structural layer coefficients of the foamed asphalt were calculated and compared to the high quality asphalt stabilized base materials used at the AASHTO Road Test. Second, equivalent thicknesses were evaluated between the foamed asphalt and a quality emulsion stabilized base material. 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 pavement temperature, surrounding layer thicknesses, loading intensities, moisture changes in the subgrade and other unbound layers, etc. The AASHTO structural coefficients are nothing more than coefficients of a regression equation relating the effects of certain specific pavement layers to pavement performance. As such, a relative evaluation of the performance of the AASHTO pavement material at the Road Test is possible.

Since the AASHTO materials have been suitably characterized in terms of their elastic properties (resilient modulus and Poisson's ratio), layered elastic models may be used to mechanistically evaluate AASHTO test sections. Furtheremore, elastic properties of foamed asphalt mixtures may be substituted for selected layers in the AASHTO layered elastic models to evaluate the changes in critical pavement mechanistic responses caused by this substitution. The result is that the critical mechanistic responses may be compared relative to their effect on performance as empirically established at the AASHTO Road Test.

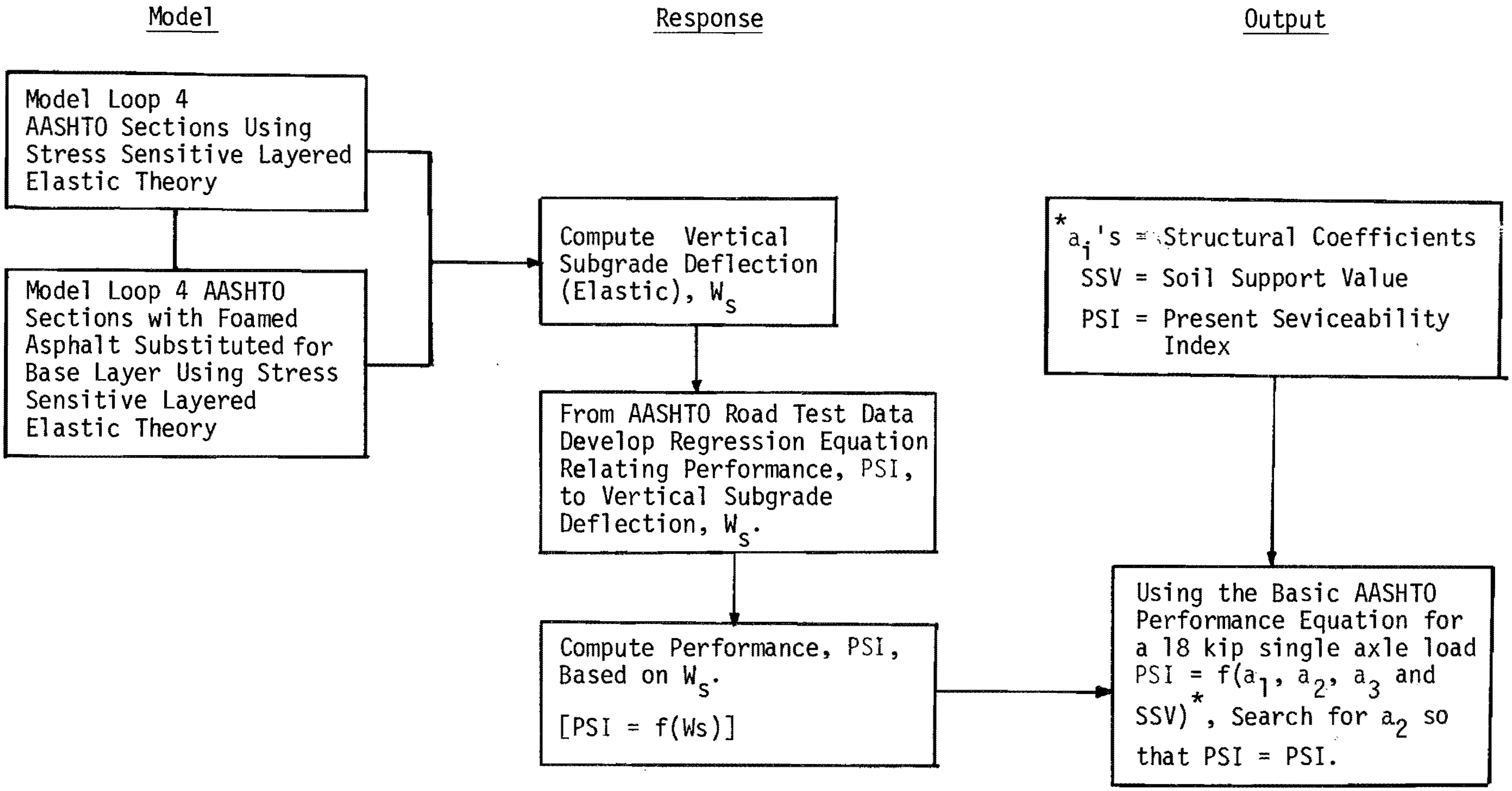
The PSAD2A stress sensitive layered elastic computer program was selected to model the AASHTO pavement sections (loop 4). The AASHTO materials were characterized elastically based on Reference 21. Figure 20 briefly illustrates the methodology used to compute structural coefficients, a_i's. The regression equation developed between the present serviceability index, PSI, and subgrade deflection, W_s, had an R^2 of 0.81 ($\alpha = 0.01$) (see Reference 22).

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 21. Note the tremendous effect of base thickness on a_2.

The a_2 values derived from this analysis are summarized in Table 4. The authors are careful to point out that these values should only be used for comparative purposes and not for design. The a_2 derived for a base thickness of 12 inches represents the value best suited for comparison to the single AASHTO value.

Note that the a_2 values presented in Table 4 are for two weighted average annual temperatures: 68°F and 82°F. These represent extremes in weighted annual pavement temperatures. The weighted average annual pavement temperature of 68°F represents Chicago, Illinois, which is near the site of the 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 climate conditions on the structural coefficient.

In order to further illustrate the meaning of the structural coefficient with respect to performance of the pavement system, the 1972 AASHTO Interim Guide for Flexible Pavement Design (23) was used to evaluate performance life of a typical Texas Farm-to-market roadway using the structural coefficients in Table 4.



*PSI' = Present severiceability of the AASHTO section containing the foamed asphalt layer which was substituted for the traditional base layer. The structural coefficient, a_2, of this layer is then computed.

Figure 20. Scheme Used to Compute Structural Layer Coefficients of the Foamed Asphalt Layers.

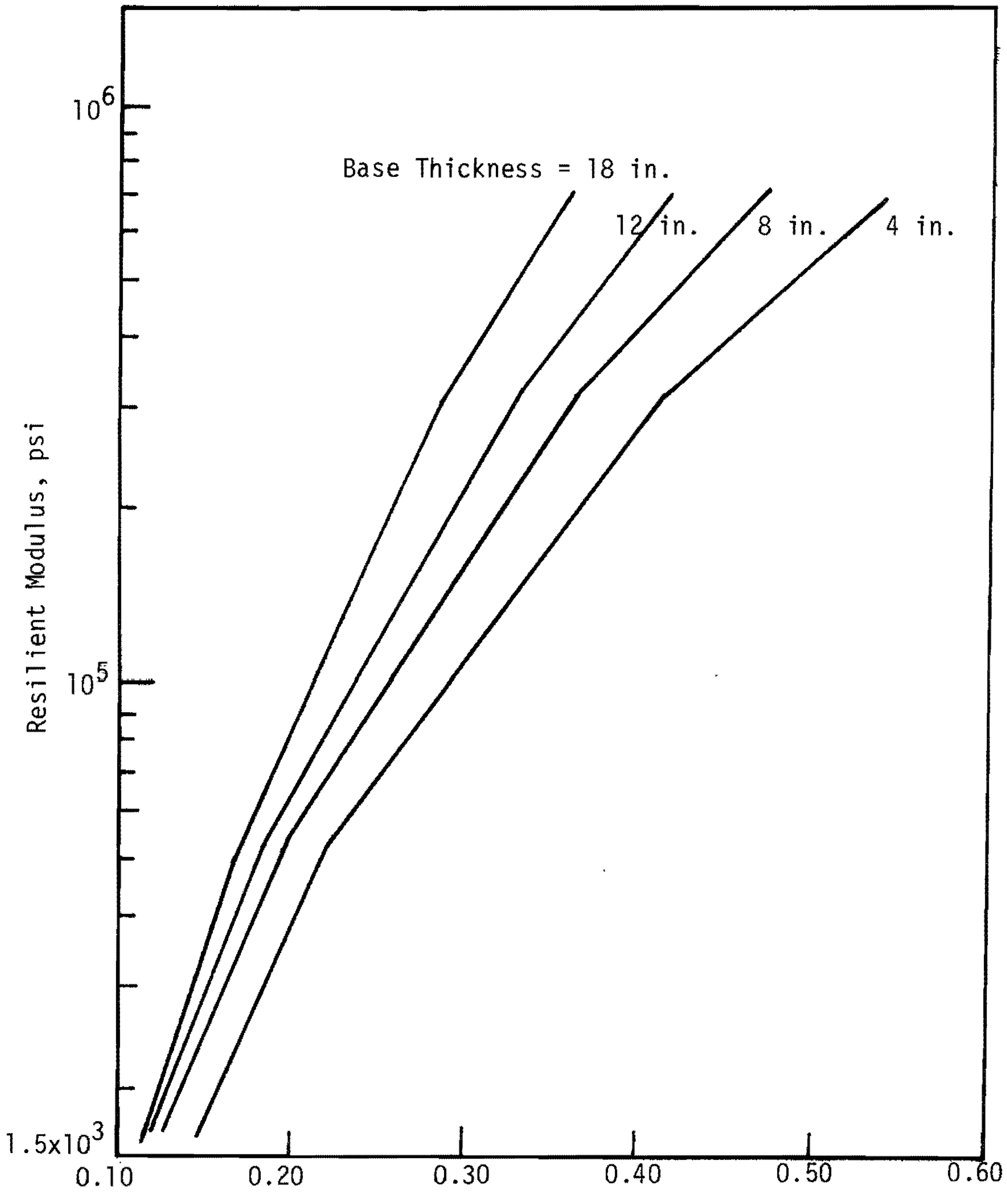


Figure 21. Relationship Between Structural Coefficient, a_2, and Average Annual Resilient Modulus.

Table 4. Structural Layer Coefficients Computed for Foamed Asphalt Materials.

Mixture Identification	Weighted Annual Pavement Temp. (°F)	Structural Layer Coefficient for Base Courses Thicknesses of (inches):				
		4	8	12	18	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

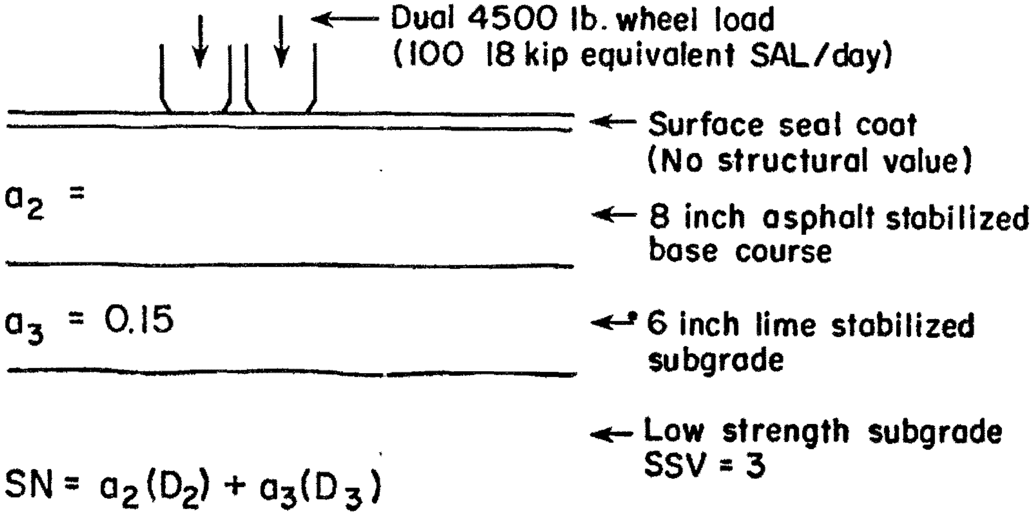
Figure 22b illustrates the results of the analysis for the pavement cross-section in Figure 22a. The essence of this analysis is that pavement performance is adversely affected by the smaller structural coefficients and resulting pavement lives are inadequate.

Perhaps a more rational scheme to compare the relative 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 equivalent thickness computation is illustrated in Figure 23. The Chevron multi-layered elastic computer program, CHEV5L (24), was used to compute the maximum ε_V under a dual 4500 lb. wheel load. Since the resilient moduli of the materials in question change with temperature, the analysis scheme encompassed equivalent thickness calculations at several pavement temperatures, several reinforcing layer thicknesses and several subgrade strengths, Figure 23. The results are summarized in Table 5.

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 criterion relative to performance, approximately 1.6-inches of foamed asphalt using District 5 aggregate is required to equal 1.0-inch of high quality HMAC base. The average equivalent thicknesses for the foamed asphalt using the other aggregates are: 1.52 for District 11, 1.84 for District 16, 1.22 for District 21 and 1.24 for the LSA mixture.

(a) TYPICAL FARM TO MARKET ROAD CROSS - SECTION



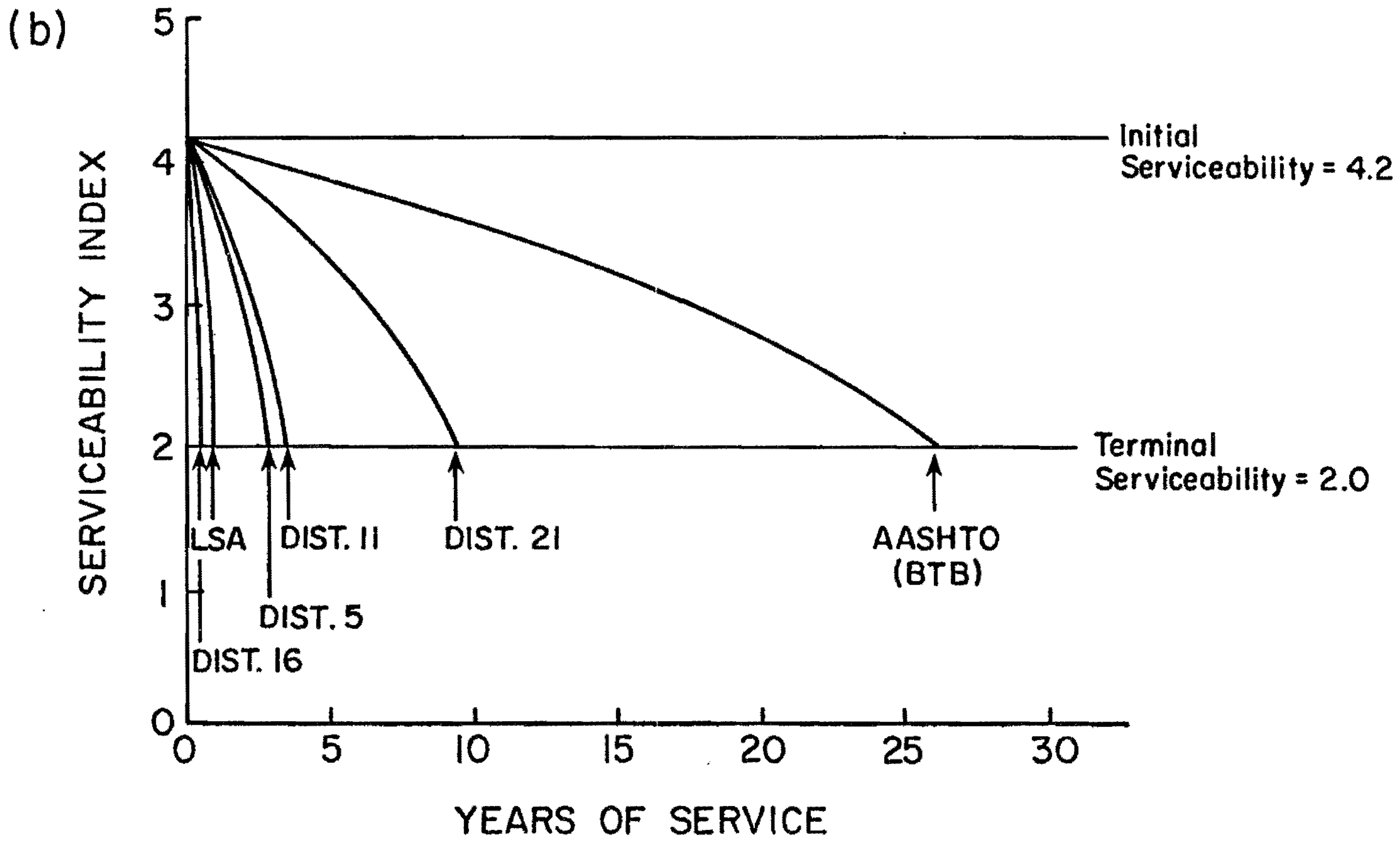


Figure 22. Effect of Structural Layer Coefficient Variation of Performance Life.

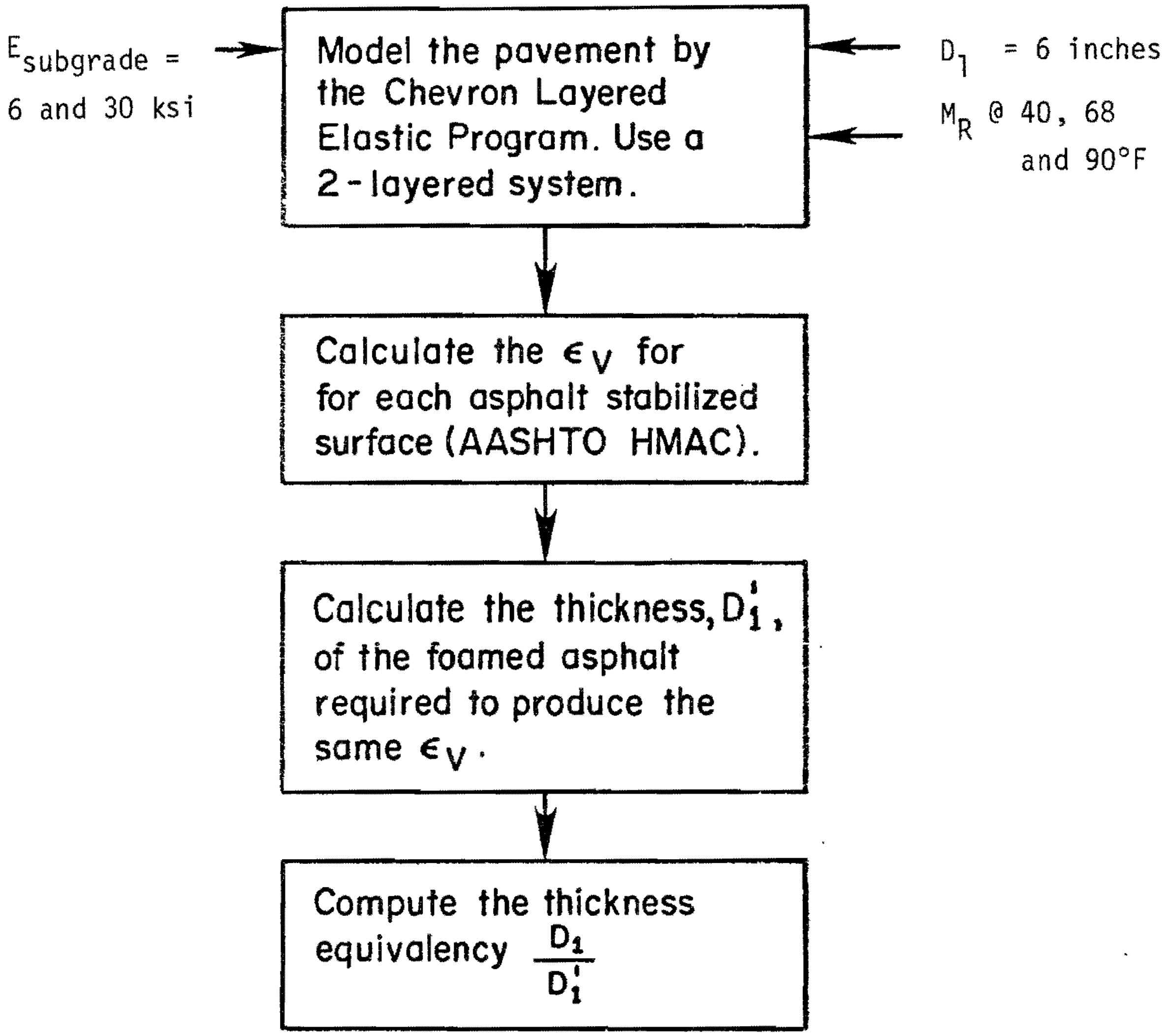


Figure 23. Scheme Used to Develop Thickness Equivalency Ratios Based on the Vertical Subgrade Strain Criterion.

Table 5. Thickness Equivalencies Based on the Vertical Subgrade Strain Criterion

Identification of Foamed Asphalt	D_1, Inches	Temp. °F	$E_{subgr.} \times 10^3$, psi	$\varepsilon_v \times 10^{-6}$	D_1', Inches	D_1'/D_1
District 5	6	68	3	780	9.93	1.65
			30	340	9.30	1.55
		82	3	1110	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	1110	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	1110	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	1110	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	1110	12.98	2.16
			30	445	10.69	1.78

RESISTANCE TO SHEARING FAILURE

As discussed previously in this section, 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 we consider full depth pavements or if we include the surface and stabilized base 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 the pavement materials. These tests are primarily a measure of the lateral pressure induced in the closed test system due to an applied vertical pressure. As such these tests are indirect indicators of the ability of the pavement materials to handle the high shearing stresses that may be developed in a pavement. A repeated or static load triaxial test would provide a better indication of shear strength. However, these tests were not part of this program.

The Hveem and Resistance value data are presented in Table C2. These results have been discussed earlier. In terms of this discussion, it will suffice to say that the resistance values are at best acceptable to marginally acceptable, based on before soak testing criteria. One would thus expect these materials to adequately resist shearing stresses encountered in well designed pavement systems. However, as with all pavement base materials, high shearing stresses can develop where pavement surface and base layers are too thin resulting in lateral deformation and rutting.

FATIGUE LIFE CHARACTERISTICS

Controlled stress beam fatigue tests were performed using foamed asphalt mixtures containing the aggregates from District 5, District 11, District 21 and the laboratory standard aggregate. Five specimens were tested at each of three stress levels. The results of the fatigue are summarized in Table 6 in the form of the well known relationship between load applications to failure, N_f, and initial bending strain, ε , where

$$N_f = K_1 \left(\frac{1}{\varepsilon}\right)^{n_1} \qquad (2)$$

Also shown in Table 6 are K_1 and n_1 regression constants developed for typical laboratory controlled stress fatigue testing of various types of potential base course materials. These results are plotted in Figure 24 for comparison.

It is obvious from Figure 24 that the fatigue properties of the foamed asphalt mixtures composed of District 21 and District 11 aggregates were the only ones to exhibit acceptable values when compared to competitive asphalt stabilized highway materials. In order to evaluate the specific implications of the fatigue properties of these mixtures, they will be further studied in the following section.

Figure 25 offers a vivid illustration of the fatigue potential of the foamed asphalt mixtures in comparison with other conventionally used highway materials. The plots on 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 25 is 10^6 repetitions. Each point identifying

Table 6. Results of Laboratory Controlled-Stress Beam Fatigue Testing at 68°F.

Material Description	K_1	n_1	R^2
(1) District 5	9.02×10^{-6}	2.290	0.94
(2) District 11	4.476×10^{-15}	4.831	0.92
(3) District 21	6.395×10^{-17}	5.229	0.74
(4) LS	4.717×10^{-3}	1.753	0.79
(5) AC Base, Colorado (15)	2.01×10^{-5}	2.69	-
(6) Sand Base, Colorado (15)	8.97×10^{-7}	3.25	-
(7) ATB (Emulsion), California (15)	8.19×10^{-7}	3.15	-
(8) Granite Stabilized with 6% AC, (Monismith) (16)	6.11×10^{-6}	3.38	-
(9) 30% Crushed Rock, 53% Sand, 9% Limestone, 8% AC (Pell) (16)	8.8×10^{-15}	5.1	-
(10) Fine Granite, 6% AC, California (16)	8.91×10^{-7}	2.95	-

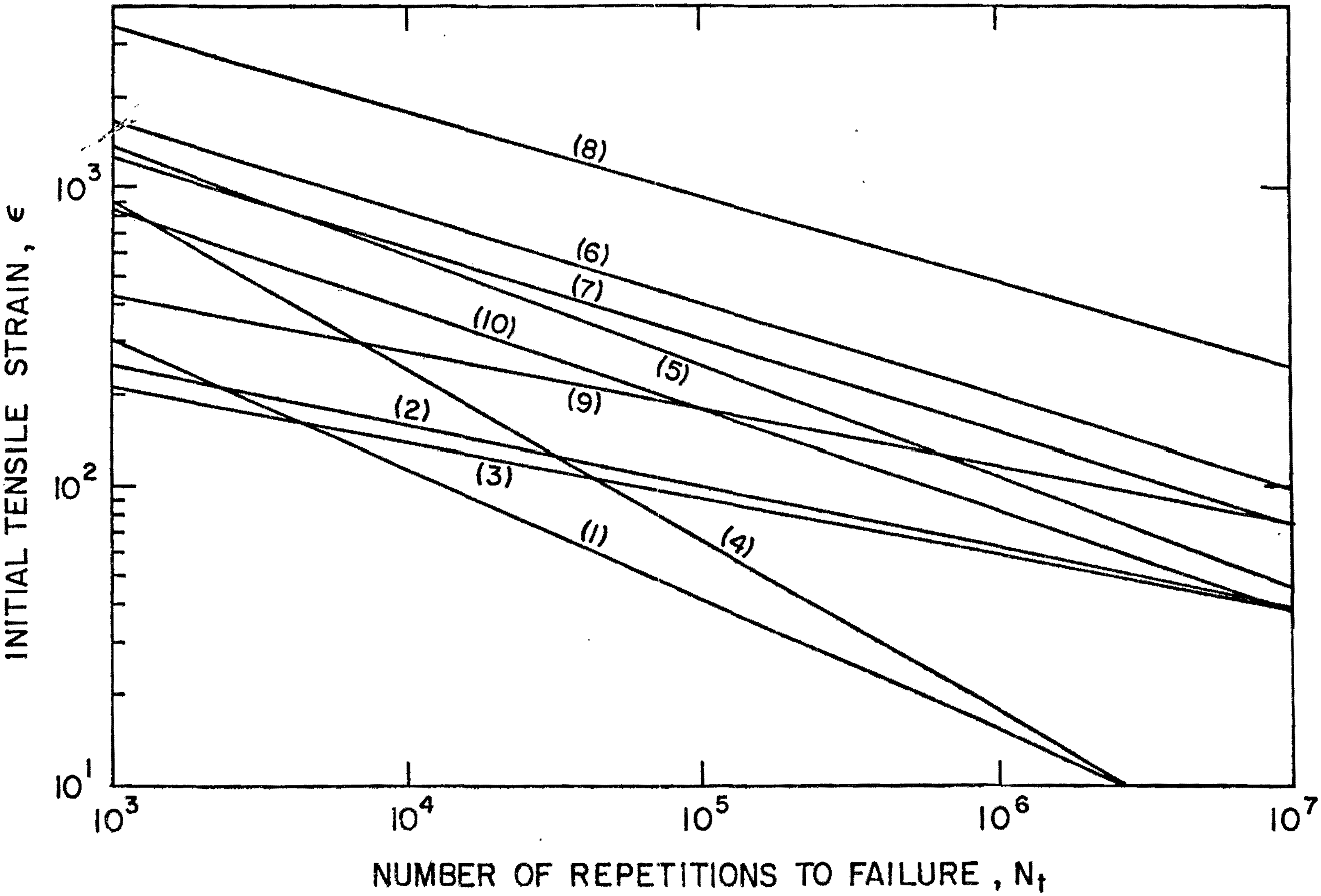


Figure 24. Laboratory Fatigue Curves Based on Table 6 Data.

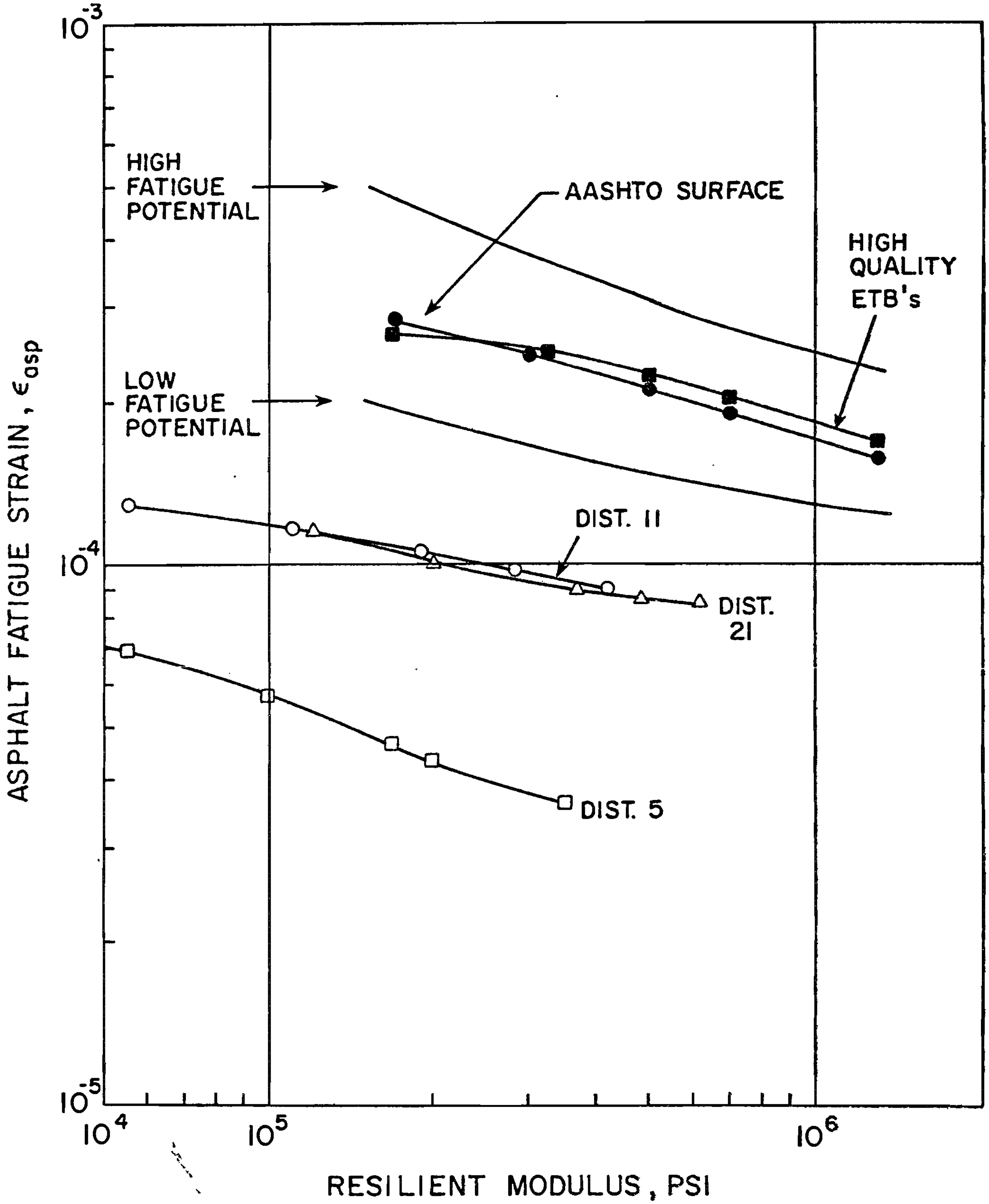


Figure 25. Permissible Asphalt Strain as a Function of Mixture Resilient Modulus (Based on 10^6 Strain Repetitions).

the respective curves describes the relationship between allowable asphalt fatigue strain and resilient modulus of the mix for a fatigue life of 10^6 repetitions.

For purposes of comparison all curves in Figure 25 have been shifted to the right to approximate field effects. The AASHTO and foamed asphalt cruves were shifted by a factor of about 13 as advocated by Finn et al., (26) for AASHTO Road Test conditions.

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

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 26 for Districts 11 and 21 foamed asphalt supplied the failure criterion while fatigue curves developed by Finn et al. (21) from laboratory tests of the asphalt stabilized materials used at the AASHTO Road Test formed the control failure criterion.

The asphalt bound AASHTO materials characterized by Finn are typical of those used to construct high quality surface and binder courses at the AASHTO Road Test. However, the fatigue properties of these AASHTO 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

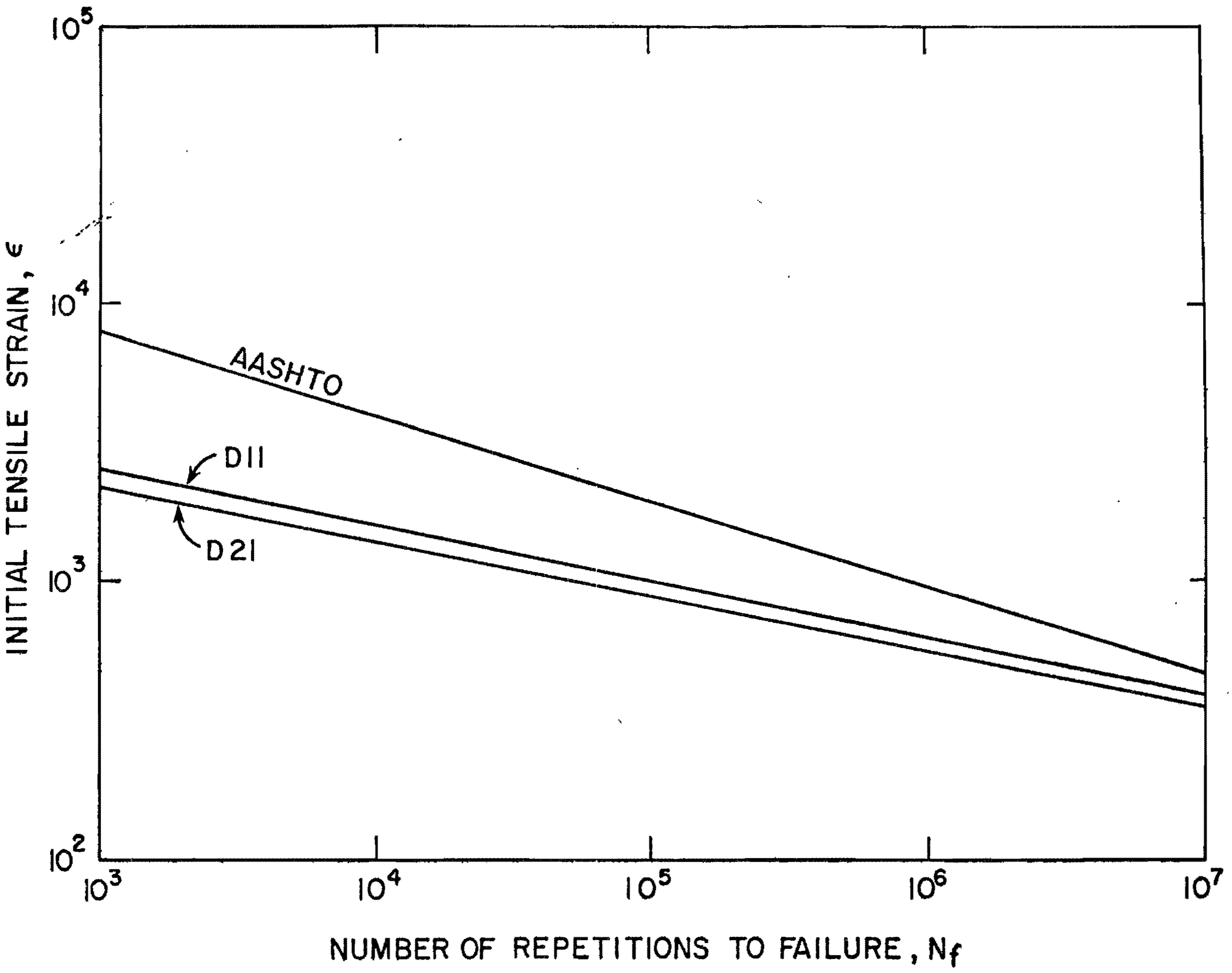


Figure 26. Laboratory Fatigue Curves at 68°F Used as Failure Criteria.

emulsified asphalt fatigue curves developed by Santucci (25). In addition, the development of the curves derived by Finn 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 AASHTO materials as developed by Finn et al. (21) is

$$\log N_f = 14.32 - 3.291 \log \left(\frac{\varepsilon}{10^{-6}}\right) - 0.354 \log \left(\frac{E}{10^3}\right) \qquad (3)$$

The general procedure was to compare the respective foamed asphalt mixtures to the AASHTO asphalt bound materials based on their fatigue properties. The index of comparison is a thickness equivalency ratio. The procedure is schematically explained in Figure 27. The layered elastic computer program BISAR was used to model the pavement structures analyzed. The fatigue characteristics, resilient moduli vs. temperature and fatigue curve-temperature shift factors are summarized in Table 7.

Tables 8 and 9 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 thicknesses 2 to 4 times greater than thicknesses 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 illustrated in Tables 8 and 9.

SUMMARY OF STRUCTURAL EVALUATION

Asphalt paving mixtures containing foamed asphalt have potential for use in upgrading the structural response of selected subgrades. A com-

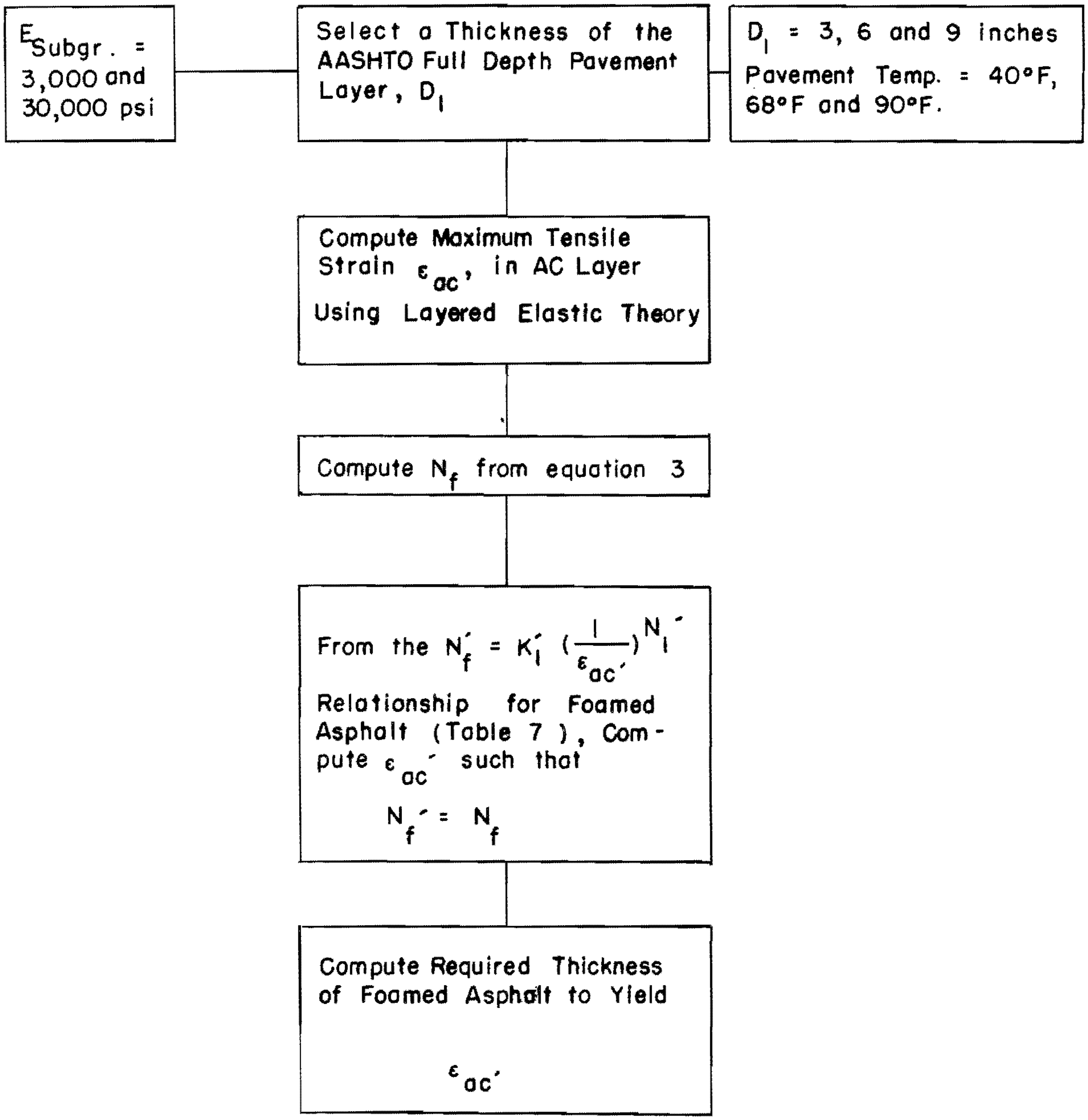


Figure 27. Scheme for Computing Thickness Equivalency Ratios Based on Maximum Tensile Strain the Asphalt Concrete.

Table 7. Fatigue Parameters Used to Develop Failure Criteria for Calculating Thickness Equivalencies.

Material Designation	Temperature, °F	Resilient Modulus, psi x 10^3	Fatigue Curve Shift Factor from 68 F	Equation of Criteria
AASHTO	68	500	——	$\log N_f = 14.82 - 3.291 \log(\frac{\varepsilon}{10^{-6}}) - 0.854 \log(\frac{E}{10^3})$
	40	1300	0.44	
	90	170	2.51	
District 11	68	190	——	$N_f = 4.476 \times 10^5 (\frac{1}{\varepsilon})^{4.831}$
	40	420	0.51	$N_f = 2.283 \times 10^{-15} (\frac{1}{\varepsilon})^{4.831}$
	90	55	2.88	$N_f = 1.289 \times 10^{-14} (\frac{1}{\varepsilon})^{4.831}$
District 21	68	370	——	$N_f = 6.395 \times 10^{-17} (\frac{1}{\varepsilon})^{5.229}$
	40	630	0.63	$N_f = 4.029 \times 10^{-17} (\frac{1}{\varepsilon})^{5.229}$
	90	120	2.62	$N_f = 1.675 \times 10^{-16} (\frac{1}{\varepsilon})^{5.229}$

Table 8. Thickness Equivalencies Based on Fatigue Failure Criteria for District 11.

Thickness of Asphalt Structural Layer, D_1 Inches	Pavement Temperature °F	$E_{subgr.}$ psi x 10^3	Equivalent Thickness of Foamed Asphalt, D_1' Inches	Equivalent Thickness Ratio D_1'/D_1
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

Table 9. Thickness Equivalencies Based on Fatigue Failure Criteria for District 21.

Thickness of Asphalt Structural Layer, D_1 Inches	Pavement Temperature F	$E_{subgr.}$ psi x 10^3	Equivalent Thickness of Foamed Asphalt, D_1' Inches	Equivalent Thickness Ratio D_1'/D_1
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

parative structural evaluation of foamed asphalt mixtures tested in this experiment and conventional asphalt stabilized base materials shows that, in general, the conventional materials can be expected to out perform the foamed asphalt mixtures. The predicted structural deficiencies of the foamed asphalt mixtures stemmed from their relatively low stiffnesses and poor fatigue resistance.

From an economic standpoint, however, foamed asphalt may have the advantage. Field research conducted by other agencies has indicated that actual pavement performance is much superior to that predicted by laboratory tests.

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 surety.

2. Paving mixtures containing foamed asphalt are generally superior to the 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 as bases or subbases if moisture susceptibility can be improved.

5. The foamed asphalt mixtures studied exhibited comparatively short fatigue lives but may be acceptable base or subbase layers in a pavement system.

6. Asphalt cement utilized in this study likely contained a silicone anti-foaming additive (see Conclusions in Appendix A). As a result, the comparatively short half-life of the asphalt foam may have been impeded by mixing with the aggregates.

7. Engineering properties of poorly graded (one-size) sands stabilized with foamed asphalt may be improved by the addition of minus number 200 mesh material.

8. Foamed asphalt mixtures would be satisfactory for in-place stabilization of existing subgrade material in order to reduce the thickness requirements of higher quality asphalt stabilized bases.

9. Foamed asphalt does not coat coarse aggregate; it concentrates in the fine material.

It should be emphasized at this point that the aggregates selected for use in this study are marginal and thus difficult to stabilize and further that much better success with foamed asphalt than that observed herein has been reported in the literature.

10. This study is based totally on laboratory molded (mixed and compacted) specimens. Lab curing procedures do <u>not</u> accurately stimulate observed field curing procedures. Thus, redistribution of the asphalt, increased strength gain, and improved water resistance may occur in the field and not in the lab. The results of this study <u>may</u> more correctly present the performance of the asphalt stabilized material between construction and final curing or "asphalt redistribution."

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Appendix A

Optimization of Asphalt Foam

OPTIMIZATION OF ASPHALT FOAM

INTRODUCTION

The primary objective of this preliminary study was to determine the asphalt cement temperature and quantity of water that would optimize the quality of the foamed asphalt. Secondary objectives were to evaluate a chemical additive designed to counteract the effects of silicone antifoaming agents and to become familiar with the operation of the laboratory model asphalt foaming device.

Foam "half-life" is defined as the time required for the asphalt foam volume to shrink to approximately one-half the original (maximum) volume. This time period was visually observed and measured with a stopwatch. Asphalt foam volume increases with the quantity of water added. However, foam half-life generally decreases as water quantity increases above one percent by weight of asphalt cement. As asphalt cement temperature increases, foam volume increases but foam life decreases. Therefore, the proper balance of asphalt cement temperature and water quantity must be utilized to optimize foam life and volume.

EXPERIMENTAL PROGRAM

The asphalt foaming apparatus described in the text of this report was operated at several conditions to produce foamed asphalt. Foamed asphalt was merely sprayed into a two pound coffee can which required only a few seconds. The maximum volume was noted and a stopwatch was started. When the foam volume decreased to approximately one-half the original value the stopwatch was stopped. The foam volume and half-life was recorded, then the weight of the asphalt cement was determined and recorded.

The AC-10 asphalt described in the Materials section of the report text was utilized throughout this study. Maximum foam volume and asphalt foam half-life was determined at temperatures of 300, 325, 350 and 375° F and at water quantities of 1, 2 and 3 percent by weight of asphalt cement. Tests were conducted at most of these conditions with and without the chemical additive AN 480 (to enhance foaming) which was supplied by Continental Oil Company. After a few preliminary tests, the appropriate quantity of the AN 480 was determined to be 0.20 percent by weight of asphalt.

RESULTS AND DISCUSSION

Results of these tests without the chemical additive are given in Table A1 and with the additive are given in Table A2. These data clearly show an increase in maximum foam volume with increasing temperature and/or water. Maximum foam volume is not appreciably affected by the addition of the AN 480, however, foam half-life is more than tripled in most cases.

Foam half-life as a function of asphalt cement temperature is plotted for six different test conditions in Figure A1. Half-life appears to increase as the quantity of water is decreased from three to one percent. In several instances an optimum temperature appears to exist around 325 F.

Tables A1 and A2 show the weight of asphalt varied in these experiments between 70 and 90 grams. In order to normalize maximum foam volume, volume-to-weight ratio was computed by dividing the maximum foam volume in cubic centimeters by the weight of asphalt in grams. Figure A2 shows volume-to-weight ratio as a function of asphalt temperature. Generally, volume-to-weight ratio increases with temperature. In most cases, volume-to-weight ratio is decreased by the addition of AN 480.

Figure A3 and A4 show the relationships between half-life and volume-to-weight ratio without and with the AN 480 additive, respectively. They are plotted to the same scale. Note the dramatic increase in half-life and significant decrease in volume-to-weight ratio when the AN 480 is used. These plots contain a great deal of information and may require careful study for full comprehension.

CONCLUSIONS

Based on the test results and observations during this preliminary program, conditions to produce foam of optimum quality were determined to include an asphalt temperature of 325 F with 2 percent water added to produce foaming and the inclusion of 0.20 percent of the additive AN 480. These conditions were employed throughout the remainder of the test program to produce laboratory test specimens from paving mixtures with foamed asphalt.

This is in agreement with published information. Bowering (AAPT) states that the type of foam found most effective is that having an expanded volume of some 10 to 15 times the volume of hot liquid bitumen which may be produced by injection of between 1 and 2 percent water. However, he further states that satisfactory foam at this expansion typically takes between two and three minutes to deflate to half its original volume. The asphalt foam utilized in this study possessed a considerably shorter half-life. This could be at least part of the reason for the relatively poor performance of the paving mixtures tested.

Representatives of Continentel Oil Company stated that the AN 480 was used strictly to counteract the effects of silicone anti-foaming additives.

Therefore, since the addition of AN 480 increased foam half-life, it follows that the laboratory standard asphalt contains silicone. The relatively short half-life of the asphalt foam used in this study could have adversely affected mixing.

Table A1 . Asphalt Foam Volume and Half-Life (No additive)

Temperature °F (°C)	Water Added, percent	Maximum Foam Volume, cc	Wt. Asphalt, grams	Vol/Wt. Ratio	Foam Half-Life, seconds
300	1	500	72	7.0	17.6
	2	750	68	11.0	22.0
	3	900	74	12.2	18.1
325	1.5	550	62	8.9	18.4
	2	850	74	11.5	13.6
	2.5	1250	90	13.9	16.5
350	1.0	500	73	6.8	27.4
	1.5	900	82	11.0	12.7
	2.0	1150	82	14.0	9.8
	2.5	1400	87	16.1	9.0
	3.0	1500	83	18.1	9.1
375	1	550	77	7.1	15.6
	2	1200	86	14.0	6.2
	3	1500	77	19.5	5.3

Table A2. Asphalt Foam Volume and Half-Life using Chemical Additive

Temperature °F (°C)	Water Added, percent	Maximum Foam Volume cc	Wt. Asphalt, grams	Vol/Wt. Ratio	Foam Half-Life, seconds
300 (149)	1	500	78	6.4	56
	2	700	70	10.0	17
	3	1000	81	12.3	11
325 (163)	1	500	79	6.3	55
	2	950	79	12.0	29
	2	900	80	11.3	—
	3	950	75	12.7	21
350 (177)	1	650	79	8.2	60
	2	800	72	11.1	30
	3	900	75	12	19

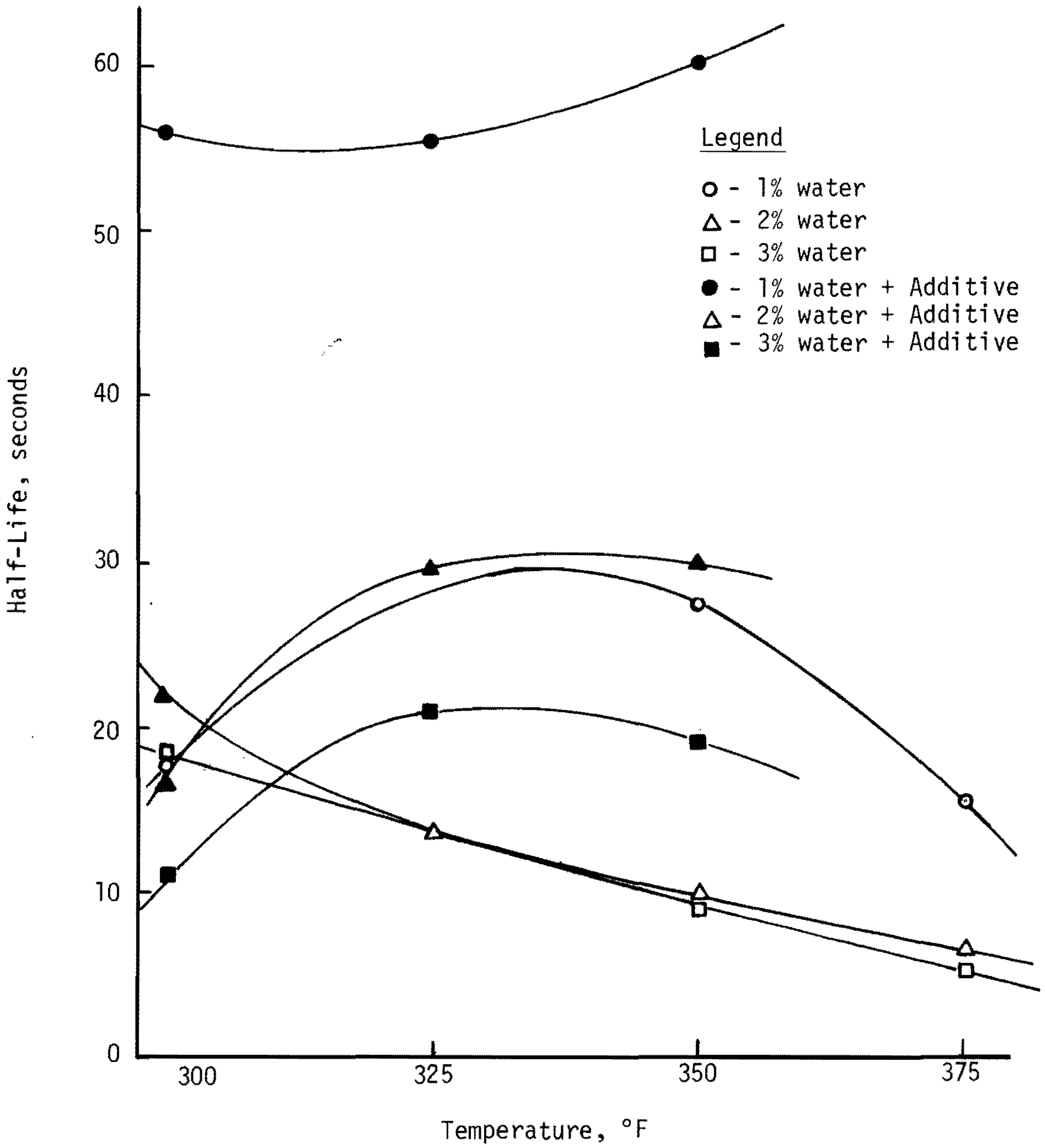

Figure A1. Foam Half-Life as a Function of Asphalt Cement Temperature

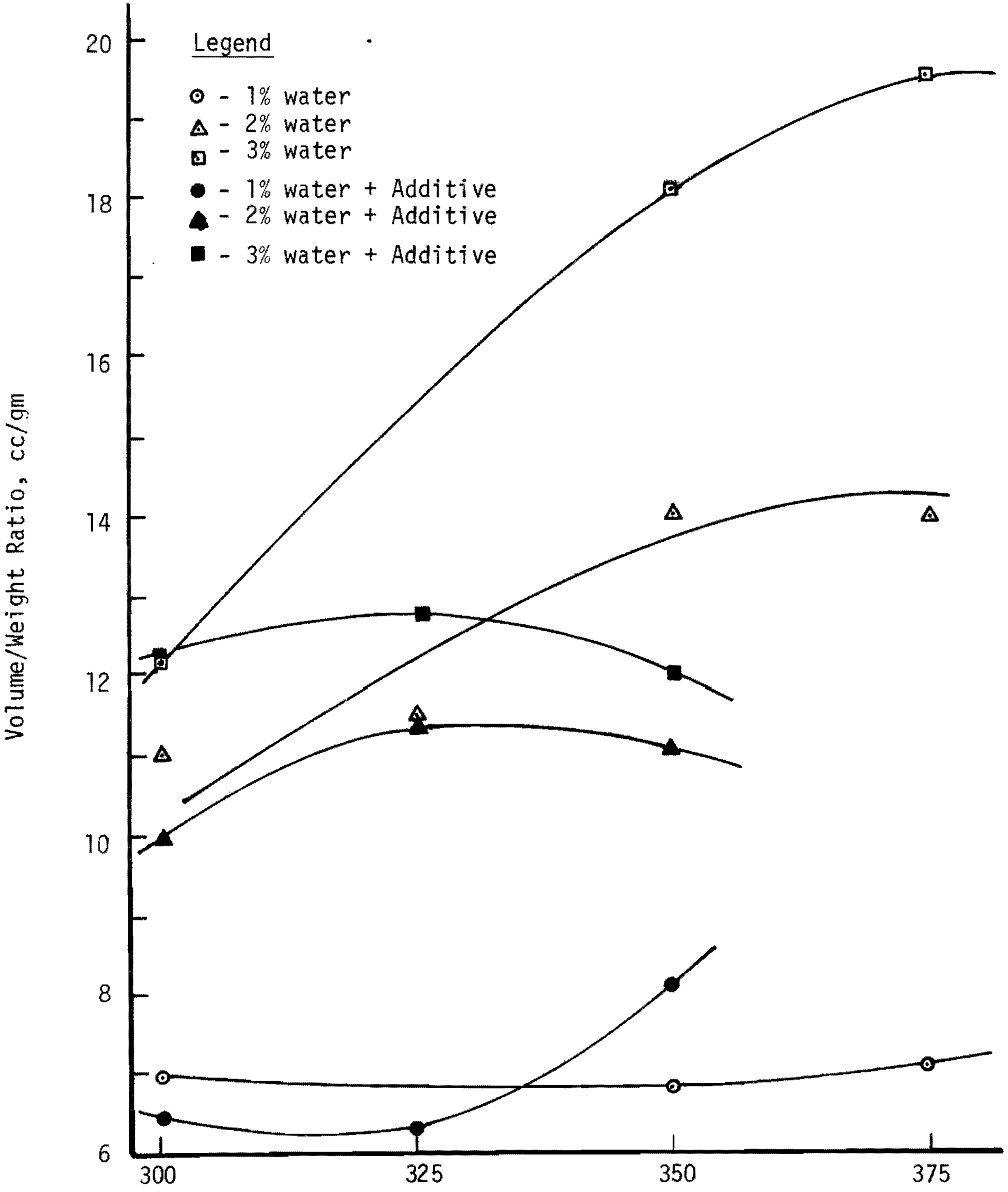

Figure A2. Volume-to-Weight Ratio of Foamed Asphalt as a Function of Asphalt Temperature

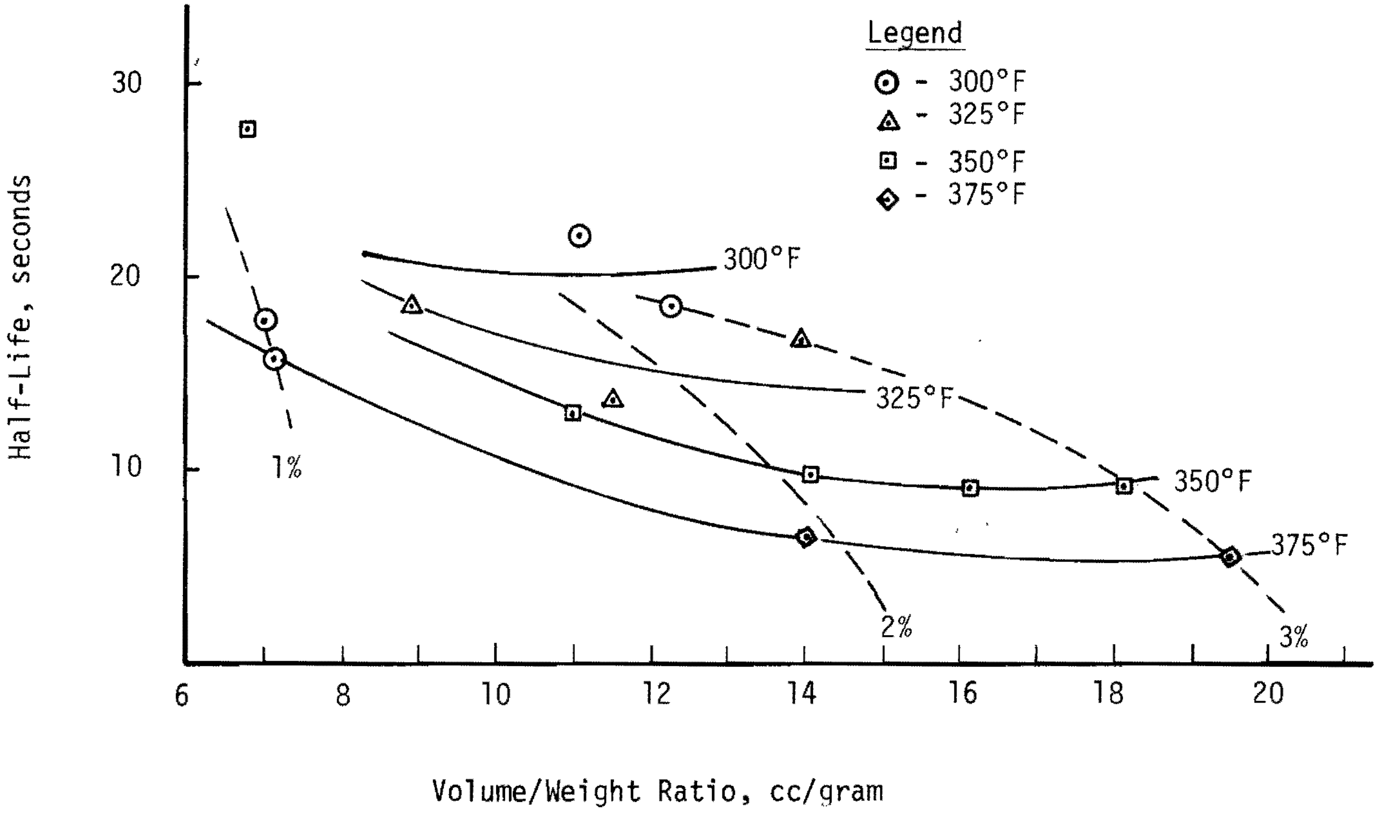

Figure A3 . Half-Life as a function of Foam Volume
<u>without</u> Chemical Additive

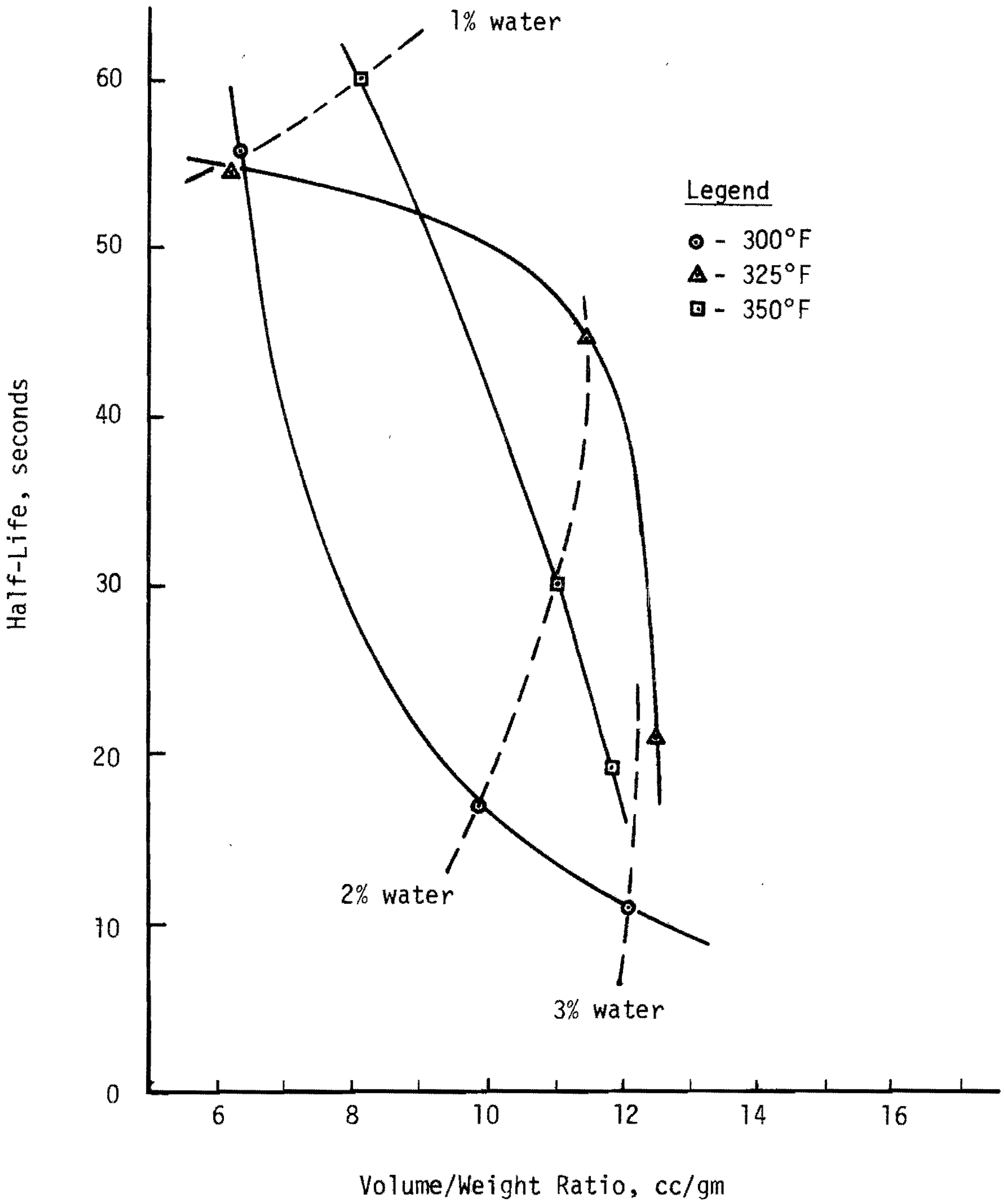

Figure A4. Half-Life as a function of Foam Volume with Chemical Additive

APPENDIX B

Materials Properties

Table B1. Summary of Asphalt Cement Properties.

Grade of Asphalt	AC-10
Viscosity @ 77°F (25°C), poise	5.8×10^5
Viscosity @ 140°F (60°C), poise	1576
Viscosity @ 275°F (135°C), poise	3.76
Penetration @ 39.2°F (4°C), dmm	26
Penetration @ 77°F (25°C), dmm	118
Penetration Ratio, %	107 (41.7)
R & B Softening Pt, °F (°C)	1.020
Specific Gravity @ 60°F (16°C)	615 (323.9)
Flash Point (COC), °F (°C)	99.9
Solubility in $C_2H_3Cl_3$, %	Negative
Spot Test	
Thin-Film Oven Test Residue Properties	
Viscosity @ 140°F (60°C), poise	3054
Penetration @ 77°F (25°C), dmm	68
Ductility @ 77°F (25°C), cm	150

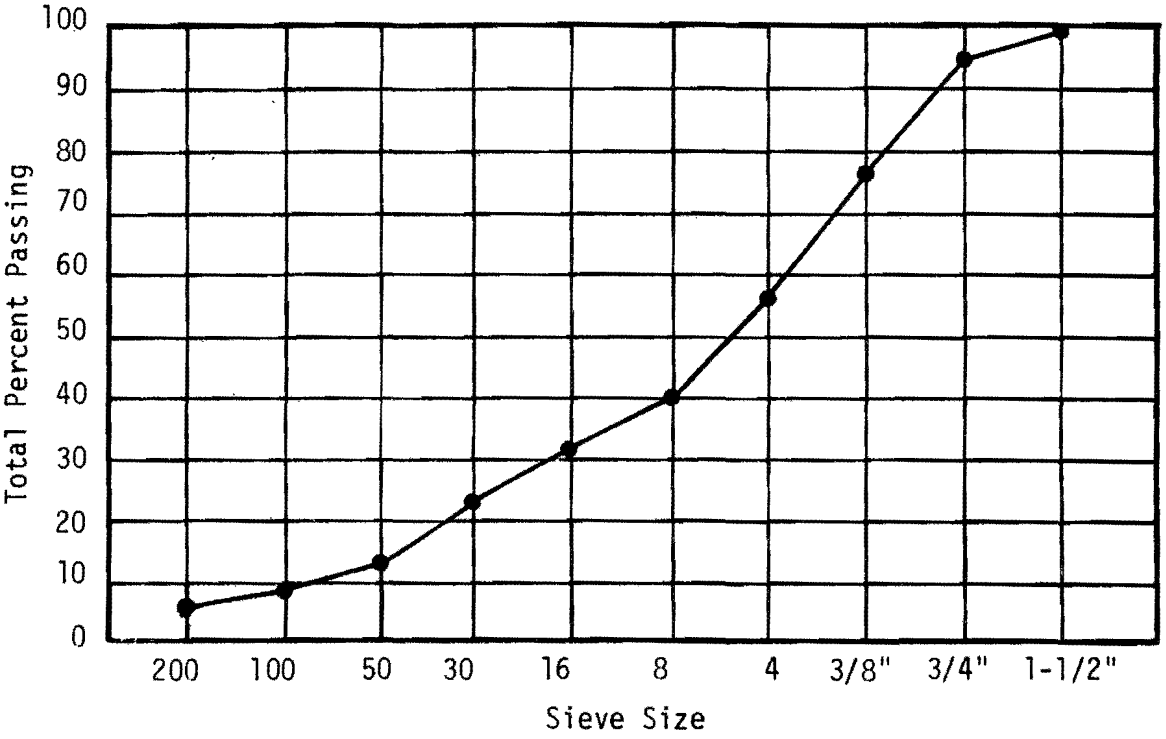

Figure B1. Sieve Analysis of Subrounded, Siliceous Laboratory Standard Gravel from District 17.

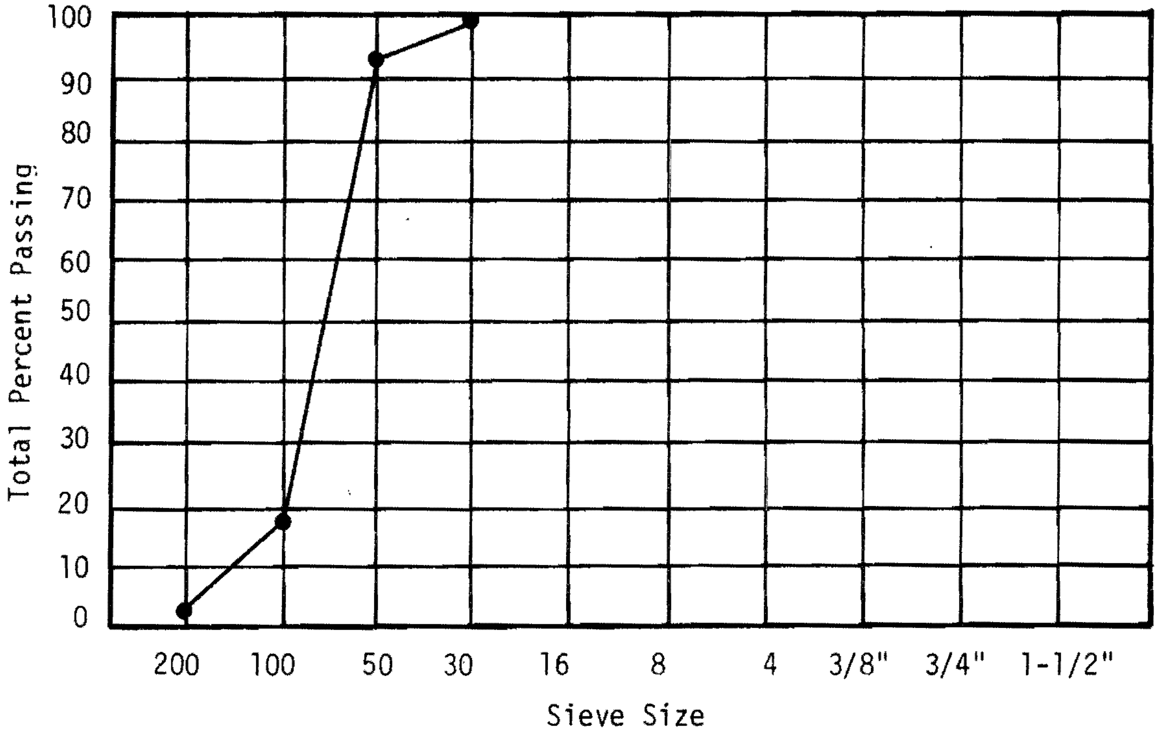

Figure B2. Sieve Analysis of Blow Sand from District 5.

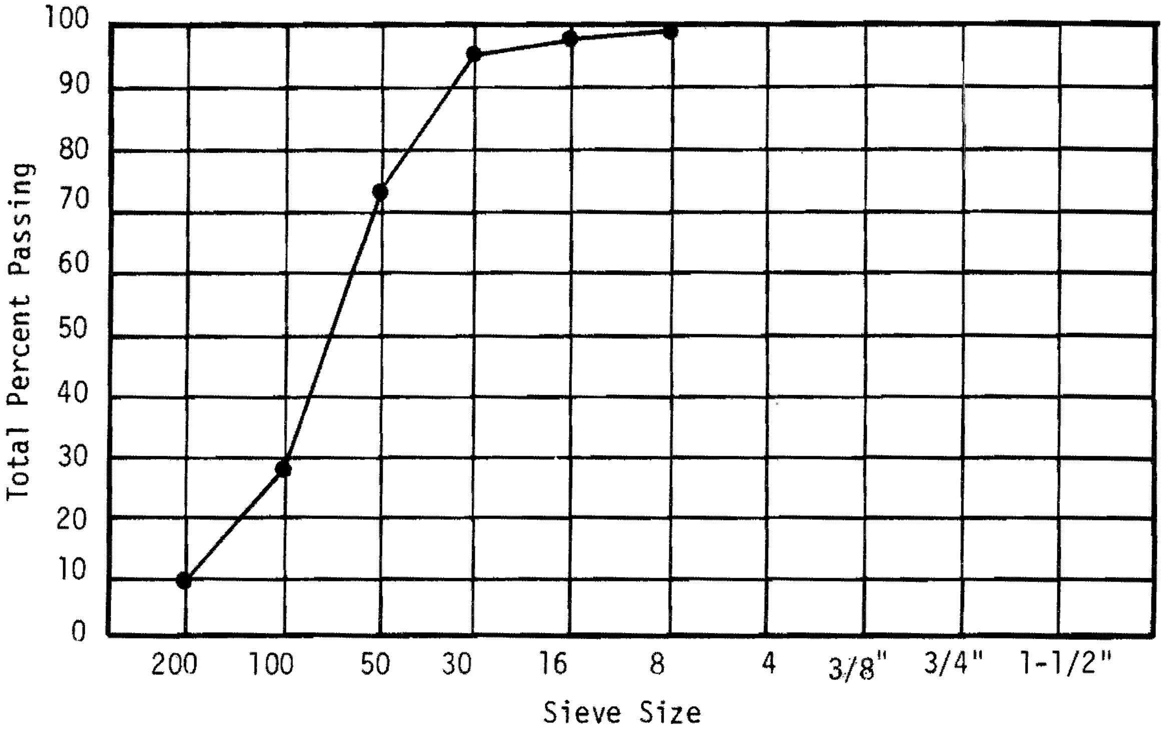

Figure B3. Sieve Analysis of Sand from District 11.

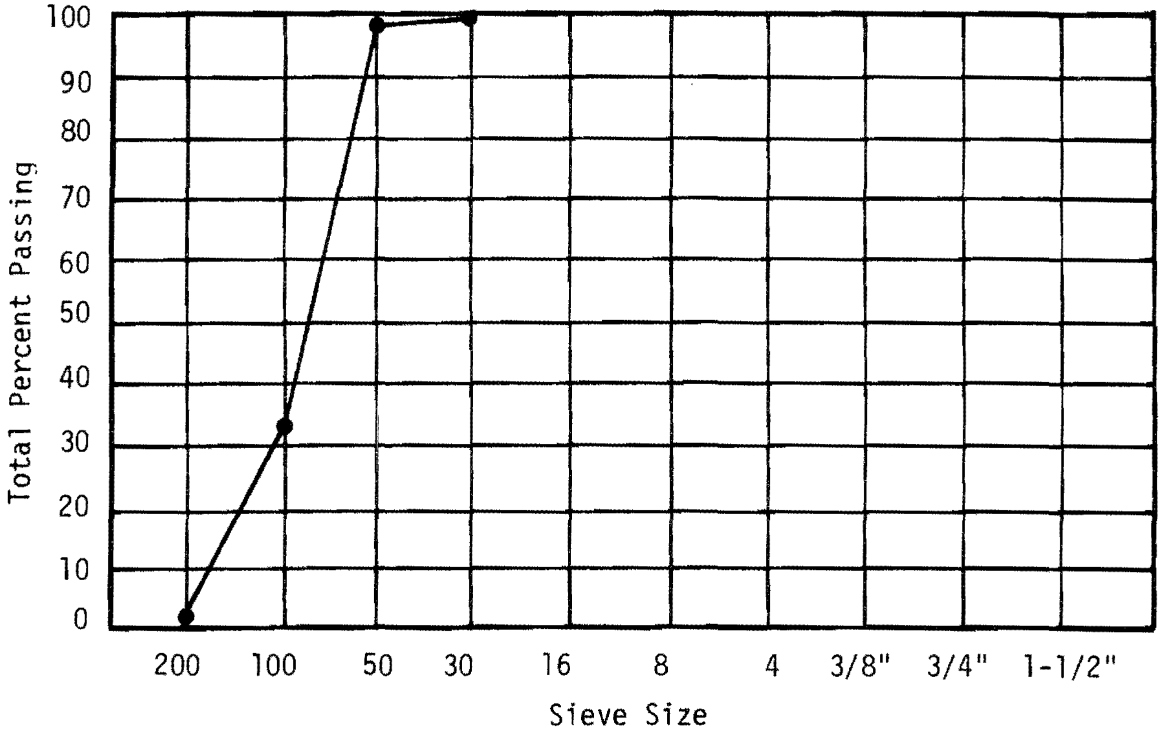

Figure B4. Sieve Analysis of Padre Island Beach Sand from District 16.

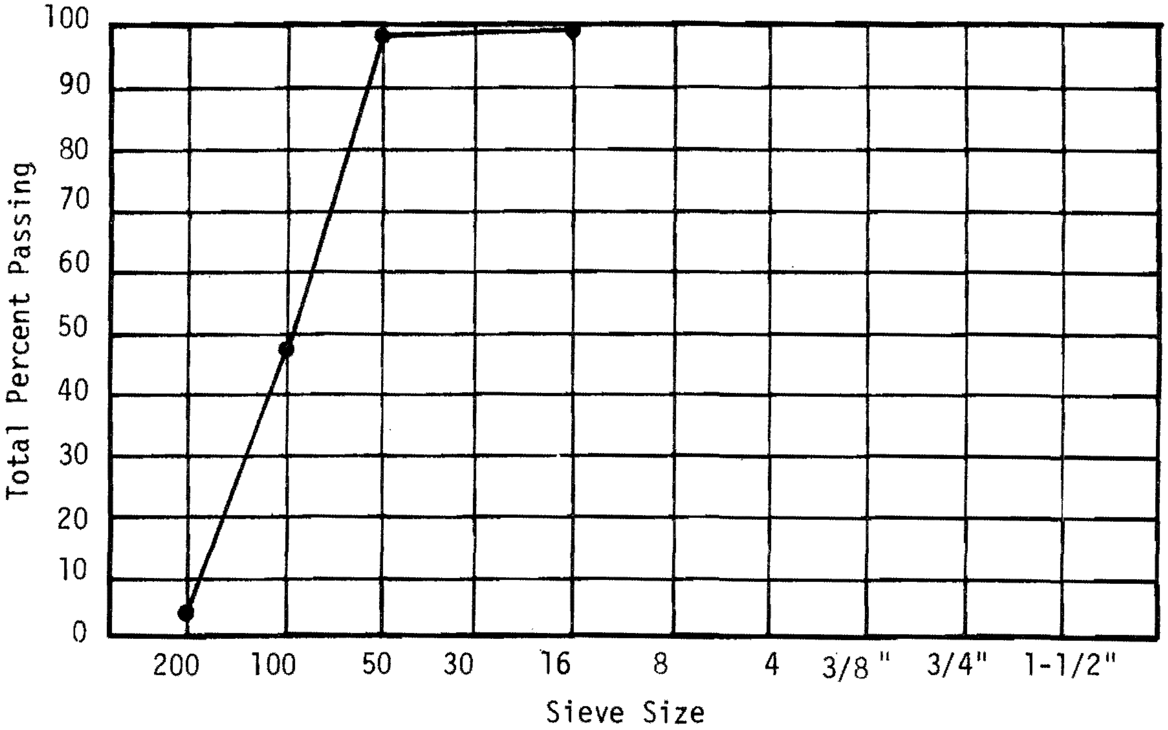

Figure B5. Sieve Analysis of Off-Beach Sand from District 21.

APPENDIX C

Mixture Test Data

Table C1. Data Summary from Determination of Optimum Foamed Asphalt Content.*

Aggregate Type and Location	Asphalt Content Wt. % Aggregate	Sample No.	After 24 Hours	After 3 Days at Room Conditions Plus 4 Days Vacuum Dessication					
			Hveem Stability @ 73°F	Hveem Stability @ 73°F	Resilient Modulus x 10^6 psi			Marshall Stability, Lbs	Marshall Flow, 0.01 Inch
					33°F	73°F	103°F		
Blow Sand Dist. 5	3.0	1A1	--	--	--	--	--	--	--
		1A2	--	--	--	--	--	--	--
		1A3	18	22	0.320	0.124	0.022	624	18
		Mean	18	22	0.320	0.124	0.022	624	18
	5.2	1B1	18	22	0.367	0.121	0.019	858	23
		1B2	18	20	0.300	0.136	0.021	1050	23
		1B3	21	29	0.343	0.150	0.024	1090	30
		Mean	19	24	0.337	0.136	0.021	1000	25
	7.2	1C1	23	28	0.280	0.112	0.014	1400	29
		1C2	23	27	0.355	0.113	0.013	1400	30
		1C3	13	25	0.367	0.063	--	1400	26
		Mean	20	27	0.334	0.096	0.014	1400	28
Field Sand Dist. 11	3.0	2A1	39	44	0.420	0.240	0.0294	1968	14
		2A2	42	47	0.408	0.210	0.0287	2016	15
		2A3	35	47	0.376	0.187	0.0298	--	--
		Mean	39	46	0.401	0.212	0.0293	1992	14

(Continued)

Table C1. Continued.

Aggregate Type and Location	Asphalt Content Wt. % Aggregate	Sample No.	After 24 Hours	After 3 Days at Room Donditions Plus 4 Days Vacuum Dessication					
			Hveem Stability @ 73°F	Hveem Stability @ 73°F	Resilient Modulus x 10^6 psi			Marshall Stability, Lbs.	Marshall Flow, 0.01 Inch
					33°F	73°F	103°F		
Field Sand Dist. 11	5.0	2B1	23	36	0.354	0.187	0.0221	2208	26
		2B2	24	42	0.516	0.176	0.0219	2592	21
		2B3	25	39	0.504	0.175	0.0226	2282	23
		Mean	24	39	0.458	0.179	0.0222	2361	23
	7.0	2C1	25	41	0.404	0.147	0.129	2547	24
		2C2	24	41	0.441	0.137	0.135	2547	24
		2C3	24	23	0.505	0.183	0.189	2714	17
		Mean	24	35	0.450	0.156	0.151	2602	21
Off-Beach Sand Dist. 21	3.1	3A1	28	44	0.442	0.219	0.0336	1745	17
		3A2	26	40	0.568	0.375	0.0478	2103	15
		3A3	23	43	0.489	0.238	0.0383	1712	16
		Mean	26	42	0.500	0.277	0.0399	1853	16
	4.8	3B1	8	35	0.727	0.328	0.0369	2457	16
		3B2	26	44	0.636	0.289	0.0346	2262	21
		3B3	21	36	0.635	0.314	0.0401	2106	18
		Mean	18	38	0.666	0.310	0.0372	2275	18

(Continued)

Table C1. Continued.

Aggregate Type and Location	Asphalt Content Wt. % Aggregate	Sample No.	After 24 Hours	After 3 Days at Room Conditions Plus 4 Days Vacuum Dessication					
			Hveem Stability @ 73°F	Hveem Stability @ 73°F	Resilient Modulus x 10^6 psi			Marshall Stability, Lbs.	Marshall Flow, 0.01 Inch
					33°F	73°F	103°F		
Off-Beach Sand	6.7	3C1	4	27	0.561	0.230	0.0212	2730	23
		3C2	17	38	0.610	0.210	0.0246	2409	20
		3C3	18	38	0.709	0.220	0.0217	2467	19
Dist. 21		Mean	13	34	0.627	0.220	0.0225	2535	21
	3.0	4A1	23	--	0.707	0.110	0.013	3120	15
		4A2	--	--	--	--	--	--	--
		4A3	--	--	--	--	--	--	--
		Mean	23	--	0.707	0.110	0.013	3128	15
	5.5	4B1	16	25	0.384	0.059	0.015	2004	26
Dense Grade River Gravel		4B2	27	40	0.999	0.146	0.054	2620	29
		4B3	28	35	1.050	0.066	0.014	2200	31
		Mean	24	33	0.811	0.090	0.028	2270	29
Dist. 17	7.0	4C1	21	29	0.831	0.086	0.015	2572	27
		4C2	26	32	1.060	0.087	0.016	2563	35
		4C3	25	39	0.897	0.103	0.024	2808	26
		Mean	24	33	0.929	0.092	0.018	2650	29

(Continued)

Table C1. Continued.

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[*] Resilient Modulus at 73°F (25°C) was not conducted after 24 hours because the test specimens were too weak to withstand the procedure.

Table C2. Mean Weights of Specimens at Various Asphalt Contents

Aggregate Type and Location	Asphalt Content, wt. % aggr.	Weight of Specimens in grams			
		Initial	After 1 Day	After 3 Days	After Vac. Des.
Blow Sand District 5	3.0	709	664	635	633
	5.2	786	752	728	724
	7.2	828	802	783	777
Field Sand District 11	3.0	683	654	646	644
	5.0	727	694	684	681
	7.0	775	743	733	730
Off-Beach Sand District 21	3.1	733	697	680	678
	4.8	781	744	727	722
	6.7	834	800	787	781
Lab. Std. River Gravel District 17	3.0	903	861	--	--
	5.5	897	858	--	--
	7.0	896	861	--	--

Table C3. Results of Tests on Paving Mixtures Made Containing Optimum Foamed Asphalt.*

Mixture	Sample Number	After 24 Hours			After Vacuum Dessication			Indirect Tensile		
		Resilient Modulus @ 73°F psi x 10^6	Hveem Stability @ 73°F	R Value @ 73°F	Resilient Modulus @ 73°F psi x 10^6	Hveem Stability @ 73°F	R Value @ 73°F	Stress, psi	Strain, in/in	Modulus, psi x 10^3
Dist 5 Blow Sand + 5.2% Asphalt	F1A	0.0090	23	69	0.375	37	91			
	F1B	0.0069	22	73	--	--	--			
	F1C	--	18	70	0.350	30	88			
	F1D	--	23	75	0.322	33	90	11	0.0043	2.5
	F1E	--	20	71	0.304	32	88			
	F1F	--	--	--	0.352	21	79	16	0.0116	1.4
	F1G	--	21	72	0.307	34	89			
	F1H	0.0067	22	69	0.346	32	91	11	0.0013	8.8
	F1I	--	--	--	0.286	25	86			
	Mean	0.0075	21	71	0.330	30	88	13	0.0057	42
Dist 11 Field Sand + 6.0%	F2A	0.0096	22	67	0.196	44	92			
	F2B	0.0067	20	66	0.200	46	94	94	0.0028	33
	F2C	0.0052	20	67	0.258	52	95			
	F2D	0.0109	21	65	0.170 (0.020)	51 (21)	94 (80)			
	F2E	0.0096	21	70	0.245	49	95	90	0.0023	39
	F2F	0.0123	20	66	0.168 (0.019)	48 (18)	93 (79)			

(Continued)

Table C3. Continued.

Mixture	Sample Number	After 24 Hours			After Vacuum Dessication			Indirect Tensile		
		Resilient Modulus @ 73°F psi x 10^6	Hveem Stability @ 73°F	R Value @ 73°F	Resilient Modulus @ 73°F psi x 10^6	Hveem Stability @ 73°F	R Value @ 73°F	Stress, psi	Strain, in/in	Modulus, psi x 10^3
Asphalt	F2G	0.0078	21	68	0.216	48	96	70	0.0018	39
	F2H	0.0058	18	65	0.253 (0.016)	52 (24)	96 (78)			
	F2I	0.0036	18	66	0.220	54	94			
	Mean	0.0079	20	66	0.214 (0.018)	49 (21)	94 (79)	85	0.0023	37
Dist 21 Off-Beach Sand + 5.2% Asphalt	F3A	0.0099	27	77	0.229	43	92	46	0.0026	18
	F3B	0.0095	25	77	0.258	41	92			
	F3C	--	26	77	0.316	32	93			
	F3D	--	28	82	0.322	38	93	36	0.0023	15
	F3E	0.0125	25	78	0.311	43	92			
	F3F	--	22	74	0.310	45	94			
	F3G	0.0115	22	76	0.265	42	94	38	0.0031	13
	F3H	--	24	75	0.276	45	94			
	F3I	--	26	77	0.276	41	92			
	Mean	0.0109	25	77	0.285	41	93	40	0.0027	15

(Continued)

Table C3. Continued.

Mixture	Sample Number	After 24 Hours			After Vacuum Dessication			Indirect Tensile		
		Resilient Modulus @ 73°F psi x 10^6	Hveem Stability @ 73°F	R Value @ 73°F	Resilient Modulus @ 73°F psi x 10^6	Hveem Stability @ 73°F	R Value @ 73°F	Stress, psi	Strain, in/in	Modulus psi x 10^3
Dist 17	F4A	0.0376	34	*85	0.069 (0.081)	44 (36)	92 (90)			
Lab	F4B	0.0431	46	80	0.136	59	93			
Std	F4C	0.0765	33	87	0.148	51	93			
+	F4D	--	42	86	0.088	60	94	66	0.0043	15
4.5%	F4E	0.0676	37	86	0.113	51	94	82	0.0040	20
Asphalt	F4F	0.0551	38	86	0.093 (0.148)	49 (31)	93 (93)			
	F4G	0.0559	30	83	0.101	49	94	73	0.0064	11
	F4H	0.0775	40	89	0.091	51	94			
	F4I	0.0721	43	89	0.101 (0.077)	61 (41)	95 (90)			
	Mean	0.0607	38	86	0.104 (0.102)	53 (36)	94 (91)	73	0.0049	16
	F5A	0.0057	19	--	--	20	67			
	F5B	0.0124	23	70	--	24	72	2	0.0043	0.5
Dist 16	F5C	0.0087	20	68	--	22	74			
Beach	F5D	0.0095	22	69	--	24	75			
Sand	F5E	0.0100	23	70	--	24	78			
+	F5F	0.0081	22	68	--	21	75			

(Continued)

Table C3. Continued.

Mixture	Sample Number	After 24 Hours			After Vacuum Dessication			Indirect Tensile		
		Resilient Modulus @ 73°F psi x 10^6	Hveem Stability @ 73°F	R Value @ 73°F	Resilient Modulus @ 73°F psi x 10^6	Hveem Stability @ 73°F	R Value @ 73°F	Stress, psi	Strain, in/in	Modulus psi x 10^3
7.0%	F5G	0.0081	22	71	--	24	74	2	0.0110	0.2
Asphalt	F5H	0.0096	22	68	--	23	76	2		0.3
	F5I	0.0099	22	69	--	22	74		0.0056	
	Mean	0.0092	22	69	--	23	74	2	0.0070	0.4
Dist 5	F6A	0.0124	27	77	0.194	43	91			
Blow	F6B	0.0087	27	79	0.145	43	92			
Sand	F6C	0.0095	27	78	0.178	45	92			
W/Silt	F6D	0.0100	28	79	0.149	42	92			
+	F6E	0.0081	28	75	0.194	41	92	61	0.0008	79
5.0%	F6F	0.0081	26	76	0.132	42	92			
Asphalt	F6G	0.0096	29	77	0.309	42	94			
	F6H	0.0099	28	78	0.124	45	93	66	0.0010	65
	F6I	0.0088	28	78	0.149	44	93	58	0.0013	46
	Mean	0.0095	28	77	0.175	43	92	62	0.0010	63
	F7A	0.0058	24	72	--	32	85	--	--	--
Dist 16	F7B	0.0060	23	75	--	32	88			
Beach	F7C	0.0066	24	74	--	30	87			

(Continued)

Table C3. Continued.

		After 24 Hours			After Vacuum Dessication			Indirect Tensile		
Mixture	Sample Number	Resilient Modulus @ 73°F psi x 10^6	Hveem Stability @ 73°F	R Value @ 73°F	Resilient Modulus @ 73°F psi x 10^6	Hveem Stability @ 73°F	R Value @ 73°F	Stress, psi	Strain, in/in	Modulus, psi x 10^3
Sand W/Silt + 7.0% Asphalt	F7D	0.0065	23	75	--	32	84			
	F7E	0.0054	23	73	--	32	84	51	0.0062	8
	F7F	0.0061	23	74	--	30	85			
	F7G	0.0068	22	71	--	28	86	25	0.0069	4
	F7H	0.0062	23	74	--	33	86			
	F7I	0.0058	24	71	--	31	86	11	0.0018	6
	Mean	0.0061	23	73	--	31	86	29	0.0048	6

*Numbers in parenthesis represent values after vacuum saturation of specimens.

Only laboratory standard aggregate and District 11 sand specimens survived vacuum saturation test.

None of the specimens survived the Lottman procedure.

Table C4. Mean Weight of Specimens With Optimum Asphalt Content.

Aggregate Type and Location	Asphalt Content, Wt. % Aggregate	Weight of Specimen in Grams			
		Initial	After 1 Day	After 3 Days	After Vac. Des.
Blow Sand Dist 5	5.2	800	769	743	741
Field Sand Dist 11	6.0	890	856	848	842
Off-Beach Dist 21	5.2	800	769	750	748
Beach Sand Dist 16	7.0	826	778	762	758
Lab. Std. Dist 17	4.5	933	921	918	916
Blow Sand + Silt	5.0	802	778	764	762
Beach Sand + Silt	7.0	834	774	758	755