THE USE OF FOAMED ASPHALT IN BITUMINOUS STABILIZATION OF BASE AND SUBBASE MATERIALS AND RECYCLED PAVEMENT LAYERS

THE USE OF FOAMED ASPHALT IN BITUMINOUS STABILIZATION OF BASE AND SUBBASE MATERIALS AND RECYCLED PAVEMENT LAYERS

L.E. Wood, A.C. Altschaeffl, C.M. Cravens Beaudoin and L.H. Castedo
FINAL REPORT

THE USE OF FOAMED ASPHALT IN BITUMINOUS STABILIZATION OF BASE AND SUBBASE MATERIALS AND RECYCLED PAVEMENT LAYERS

To: Harold L. Michael, Director
Joint Highway Research Project
March 14, 1984

From: A. G. Altschaeffl
Research Engineer
Project: C-36-21E
File: 2-8-5

Please find attached the Final Report for the HPR Part II study, "The Use of Foamed Asphalt in Bituminous Stabilization of Base and Subbase Materials and Recycled Pavement Layers." The report was authored by L. E. Wood, A. G. Altschaeffl, C. M. Cravens Beaudoin, and L. H. Castedo of our staff.

The report is presented in 2 parts. Part I is an overview of the project and summarizes task findings. Foamed asphalt is a good stabilization material when the selected asphalt has optimal foaming qualities. Excellent Marshall stabilities were obtained, even with recycled material. The design procedures developed for foamed mixtures are contained herein.

Part II represents the detailed report on Task B on the durability of the foamed mixtures to: 1) soaking in water; 2) cycles of soaking and freezing and thawing. Three additives to improve durability were examined: 1) lime; 2) indulin; 3) silane. The non-destructive pulse-velocity test gave results that appear to be related to Marshall stability; it shows great promise for further use. Durability, strength, and longevity were improved by the lime to such an extent that generally less suitable materials (e.g., pit-run gravel or outwash sand) rival better material (e.g., crushed limestone).

We believe foamed asphalt is a viable alternative material for bituminous stabilization.

This report is submitted for review and approval as evidence of fulfillment of the objectives of this project.

Respectfully submitted,

A. G. Altschaeffl
A. G. Altschaeffl, P.E.
Research Engineer

cc: A.G. Altschaeffl
    J.M. Bell
    W.F. Chen
    W.L. Dolch
    R.L. Eskew
    J.D. Fricke
    J.R. Skinner
    W.H. Goetz
    G.K. Hallock
    J.F. McLaughlin
    R.D. Miles
    P.L. Owens
    B.K. Partridge
    C.F. Scholer
    R.M. Shanteau
    K.C. Sinha
    C.A. Venable
    L.E. Wood
    S.R. Yoder

J.D. Fricker
G.K. Hallock
J.F. McLaughlin
R.D. Miles
P.L. Owens
B.K. Partridge
C.F. Scholer
R.M. Shanteau
K.C. Sinha
C.A. Venable
L.E. Wood
S.R. Yoder
**Title:** The Use of Foamed Asphalt in Bituminous Stabilization of Base and Subbase Materials and Recycled Pavement Layers

**Abstract:**

Part I of this report is an overview of this project. It summarizes the task findings. The foaming characteristics of asphalt must be established by tests for foaming volume and foam life in order to find that optimum asphalt for use. With recycled material, excellent Marshall stabilities were obtained. Detailed mix design procedures were created for foamed mixtures, and these are contained herein. Somewhat lower asphalt contents were required with foamed mixtures, but water-sensitivity durability appeared to be low.

Part II represents the detailed report on the study of the durability of the foamed asphalt mixtures relative to a) soaking in water; b) cycles of soaking and freezing and thawing. Asphalt contents "at-optimum" and 1 percent above optimum were used as were 3 additives to improve durability: a) lime; b) indulin; c) silane. The non-destructive pulse-velocity test gave results that appear to be related to Marshall stabilities; it showed great promise for use in such studies. Durability, strength, and longevity were improved with 1-2 percent lime additives to such an extent that generally less suitable material (e.g., pit-run gravel, or outwash sand) may rival a generally more suitable material (e.g. crushed limestone).

Foamed asphalt does appear to be a viable alternative material for bituminous stabilization.

**Key Words:** Foamed asphalt; bituminous mixtures; mix design; durability; water sensitivity; additives; freezing and thawing; pulse-velocity; Marshall stability;
FINAL REPORT

THE USE OF FOAMED ASPHALT IN BITUMINOUS STABILIZATION OF BASE AND SUBBASE MATERIALS AND RECYCLED PAVEMENT LAYERS

by

L. E. Wood
and
A. G. Altschaeffl
Professors of Civil Engineering
and
Christine M. Cravens Beaudoin
and
L. Humberto Castedo
Graduate Instructors in Research

Joint Highway Research Project

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Prepared as Part of an Investigation

Conducted by

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Engineering Experiment Station
Purdue University

in cooperation with the

Indiana Department of Highways

and

Federal Highway Administration
U. S. Department of Transportation

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data reported herein. The contents do no necessarily reflect the official views in policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Purdue University
West Lafayette, Indiana

March 14, 1984
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGHLIGHT SUMMARY</td>
<td>vii</td>
</tr>
<tr>
<td><strong>PART I</strong></td>
<td></td>
</tr>
<tr>
<td><strong>PROJECT OVERVIEW</strong></td>
<td></td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>PROJECT CHRONOLOGY</td>
<td>5</td>
</tr>
<tr>
<td>TASK SUMMARIES</td>
<td>8</td>
</tr>
<tr>
<td>Task A - Development of Mix Design Procedures</td>
<td>8</td>
</tr>
<tr>
<td>Task B - Durability Characteristics of Foamed Asphalt Mixtures</td>
<td>10</td>
</tr>
<tr>
<td>Task C - The Use of Foamed Asphalt for Cold Mixed Recycled Bituminous Pavement Mixtures</td>
<td>13</td>
</tr>
<tr>
<td>MAJOR FINDINGS</td>
<td>16</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>27</td>
</tr>
<tr>
<td>LABORATORY MIX DESIGN PROCEDURE FOR FOAMED ASPHALT MIXTURES</td>
<td></td>
</tr>
<tr>
<td>List of Tables</td>
<td>29</td>
</tr>
<tr>
<td>List of Figures</td>
<td>29</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>30</td>
</tr>
<tr>
<td>2. Aggregate Quality Evaluation</td>
<td>31</td>
</tr>
<tr>
<td>3. Foamed Asphalt Evaluation</td>
<td>35</td>
</tr>
</tbody>
</table>
Highlight Summary

This is the final report for this project. There are two parts to this report. Part I contains a general overview of the project history; the three tasks are briefly summarized, and the major findings are assembled in the hope they may be implemented. Part II is the detailed report covering the study of the durability of the foamed asphalt mixtures; this Part covers Task B of the project, while Tasks A and C were covered by reports previously issued.

The project was motivated by concerns of economy as bitumen became more costly. In addition, bituminous stabilization also faced environmental concerns on hydrocarbon emissions. It was an appropriate time to investigate the use of foamed asphalt, a relatively new stabilization material. This material offered several benefits to answer the concerns being raised.

The foamed asphalt process involves foaming by injecting cold water into the hot asphalt cement and spraying the foam onto the aggregate while mixing in a
mixing chamber. The asphalt appears to coat the fines, and can be applied to moist, cold aggregate.

Three aggregates were used for the investigation, a crushed limestone, a pit-run gravel, and an outwash sand. An AC-20 asphalt cement was selected because of its optimum foaming volume and foam life from among the asphalts available commercially in Indiana. This examination constituted a major part of Task C. It was found that asphalts must be tested to establish foaming quality; kinematic viscosity of foaming temperature was not sufficient parameter, by itself. The foamed asphalt was applied to a recycled mix. Excellent Marshall stabilizations were obtained with 0.5% and 1.0% foamed asphalt added.

Mix design procedures were created by Task A. It was found that foamed asphalt, indeed, can create quality stabilized base course materials. Procedures are relatively simple, no dilutants are added, no aeration is required prior to compaction, cold mix bases can be produced with cold and wet dirty aggregates and the mix can be stockpiled. The data suggested that the same or higher stability values can be achieved with lower asphalt contents than conventional mixes. However, water sensitivity durability appeared to be low. These laboratory procedures for mix design are part of this report.
Task C examined the durability of the three aggregate materials relative to: (1) soaking in water; (2) cycles of soaking in water, freezing and thawing. Asphalt contents "at-optimum" and 1 percent above "optimum" were used. Three additives were also examined to see if durability would be improved: (1) lime; (2) indulin; (3) Silane.

From the durability testing, it was found that the additives enabled the mixes to retain more of their original stability. Lime was consistently the additive that produced the best performing mix (at 1.0% and 2.0% additives). The improvement was sufficiently large that a material generally less suitable (e.g., outwash sand and pit-run gravel) gains so much as to rival a material more suitable for bituminous mixes (e.g., crushed limestone). In addition, resistance to the action of water was also markedly improved.

Task B monitored deterioration with a variety of techniques. Only the non-destructive pulse-velocity test produced results that appear well-related to the rate of deterioration shown by Marshall stability values. The pulse-velocity test is thought to show large promise as a non-destructive test to monitor changes in stability.
The investigators believe foamed asphalt is a quality viable alternative technique for bituminous stabilization.
PART I

PROJECT OVERVIEW
PART I
PROJECT OVERVIEW

Introduction

This report represents a summary of the work done by the researchers on this project. It attempts to show that the project, indeed, fulfilled its objectives.

This project has dealt with a relatively new stabilization material, foamed asphalt. As bitumen has become more expensive, bituminous stabilization of base and subbase and recycled pavement materials have also become more expensive. In addition, environmental concerns have been raised about the emission of hydrocarbons during curing of the conventionally stabilized mixtures. The new agent, foamed asphalt, appears to positively overcome some of the questions being raised.

The foamed asphalt process involves foaming the asphalt by injecting cold water into the hot asphalt cement and spraying the foam onto the aggregate while mixing the two in a mixing chamber. The resulting mix
can then be placed, compacted, and used without a major curing period. It has been noted that the asphalt appears to coat the fines in the mix (rather than the coarse particles) making the presence of significant fines a major benefit. The aggregate can be cold and moist when sprayed with the foamed asphalt. There is no major curing period because there was added no material necessary to allow coating to occur. The components of the mix stay in the mix.

The foregoing suggested several potential benefits from using foamed asphalt as a stabilizing agent: 1) lesser asphalt contents appear to be possible; 2) lesser energy use is required because there is no aggregate heating; 3) aeration of mix is unnecessary; 4) much lesser emission of hydrocarbons occurs from the mix; 5) lesser haulage costs are incurred because no excess water is present in the mix; 6) more marginal materials may become candidates for use.

The potential benefits appeared to be of sufficient promise to warrant a closer examination of the behavior of the mixtures that could be created. This project was formed to examine these mixtures. Foaming characteristics of the asphalts available needed to be addressed, for the better the foam and its life, the better would be the insertion of the asphalt into the aggregate. Materials were selected to represent the
range of aggregates used by IDOH, including such generally less suitable materials as pit-run gravel and outwash sand. Mix design procedures were revamped to accommodate the foamed asphalt. These procedures are presented in a later section of this Part I of this report.

In previous work conducted using foamed asphalt mixtures, it was noted that the voids in these mixtures appeared to be larger than those in conventionally stabilized mixtures. This motivated a major examination in this project of the durability of the mixtures, as well as ways to overcome durability sensitivity.

Part I of this report also contains a brief chronology of the development of the project and the "milestones" in its progress. This is followed by a brief summary of each of the component tasks in the manner of an overview. The major findings of the project (including mix design procedures) are then presented as matters which can be used in practice.

Part II of this report represents the detailed report on the durability of foamed mixtures (Task B of the project). It contains these details because, unlike the other material of the project, this information was not presented in an Interim Report of the project. Part II can stand independently as a report on
durability characteristics. It is presented herein for convenience.
The proposal entitled "The Use of Foamed Asphalt in Bituminous Stabilization of Base and Subbase Materials and Recycled Pavement Layers" was prepared and transmitted on May 18, 1979. It contained three tasks. The proposal was approved for funding beginning September 1, 1979 (under letter dated September 14, 1979 from Mr. M. J. Monahan) with a completion date of June 30, 1983. Additional correspondence occurred about completion date, and a date of June 30, 1984 was approved on February 6, 1980.

An Interim Report was approved May 7, 1981 for Task C of the project, as entitled, "A Laboratory Investigation on the Use of Foamed Asphalt for Recycled Bituminous Pavements" by M. Brennan (Report No. FHWA/IN/JHRP-81/5, March, 1981).

In Task A it was found impossible to create reasonable mixes with one of the four aggregates suggested in the original proposal. Accordingly, a revision in the Work Plan for Task A was requested. Under letter
of April 13, 1981, the revision was considered minor and did not require specific approval.


The investigators reviewed the results of findings from Tasks A and C with respect to the experimental program for Task B. A revised Work Plan for Task B was requested; by letter of April 27, 1982 it was stated that the revision was considered minor and did not require specific approval.

It must be noted, and acknowledged, that a test section using a foamed asphalt recycled mix basic course was constructed by IDOH in 1981 on a portion of SR16 rehabilitation. A companion JHRP study was initiated under the direction of Professors E. J. Yoder and L.E. Wood to examine performance. A report of that study has been approved, as entitled, "Determination of the Structural Coefficients of a Foamed Asphalt Recycled Layer," by A. Van Wijk (Report No. JHRP-84-1, January 1984).

This final report of the project (also containing the findings of Task B) was presented May 1, 1984 as
TASK SUMMARIES

TASK A - DEVELOPMENT OF MIX DESIGN PROCEDURES.

Introduction

A detailed laboratory investigation was performed to characterize the performance of foamed asphalt as a stabilizing agent of pavement materials. The objectives were to develop guidelines for a mix design procedure. The effects of different variables on foamed asphalt mix behavior were investigated using a base asphalt and previously selected aggregates. This research produced an outline of the selection, proportioning and testing of components for foamed asphalt mixtures.

Experimentation

Foamed asphalt was produced using AC-20 as the bituminous material and outwash sand, pit-run gravel and crushed limestone as the aggregates.
The variables studied were: bitumen content (3 levels); mixing moisture (3 levels); curing period (3 levels); testing temperature (2 levels); and mixing temperature (3 levels).

Three replicate samples were prepared introducing foamed asphalt to moistened aggregate at room temperature. After a mixing period, specimens were compacted by use of the kneading compactor and were cured for an appropriate period. Resilient modulus, modified Hveem stabilometer, and modified Marshall stability tests were performed on dry and water saturated samples.

Conclusions

The foamed asphalt mixtures investigated in this study demonstrated that bitumen and moisture content at time of mixing greatly influence the mixture performance. The "fluff point" of the aggregate proved to be an ideal water content for mixing purposes. Strength and stability values for all tests were greater at the lowest testing temperature. Foamed asphalt mixes were found to be significantly affected by water infiltration. Water sensitivity results indicated that saturated strengths and stabilities were much lower than corresponding cured values. Specimens prepared at the highest bitumen content showed a greater resistance to water. Foamed asphalt mix strength also increased with curing time, particularly from 1 to 3 days.
**TASK B – DURABILITY CHARACTERISTICS OF FOAMED ASPHALT MIXTURES.**

**Introduction**

Durability characteristics of three foamed asphalt mixtures were examined with respect to water sensitivity and to cyclic freezing and thawing. Information gained in Task A was used to establish the choice and level of the several variables involved in this study. It was found in Task A and during this research that the untreated mixtures exhibited significant losses in stability with exposure. Three different additives were incorporated into the foamed asphalt mixtures to possibly mitigate these detrimental effects. Techniques were developed to establish the various weathering conditions as well as methods to monitor their effects on the samples.

**Experimentation**

The variables identified in Task A were incorporated in this durability study, namely: three aggregates (outwash sand, pit-run gravel and crushed limestone); one base asphalt foamed at two different levels ("at-optimum" condition and 1 percent above "optimum"). Three additives were examined to observe if they would
improve the durability behavior, viz. lime, indulin, and silane. The lime and silane were incorporated directly into the aggregate during an initial mixing phase while the indulin was added to the asphalt prior to foaming.

The exposure conditions consisted of cycles of water saturation and of cycles of water saturation and freezing and thawing. The effects of these conditions were monitored by non-destructive tests such as pulse-velocity, resilient modulus and change in weight of the sample; a modified Marshall stability (at 72° F), was also used.

**Conclusions** It was found that vacuum saturation (water sensitivity test) weakened all the specimens. The additives enabled the pit-run gravel and outwash sand to retain much more of their original stability, while they had little effect on the crushed limestone.

Higher levels of asphalt content appeared to create slightly better water sensitivity behavior. Lime and silane additives resulted in better water resistance than would have been possible by the addition of more asphalt alone.

Cyclic freezing and thawing also weakened all the specimens. Additives enabled the samples to retain
more of their original stability than did the untreated specimens. The additives also appeared to create a larger cyclic longevity. Lime was consistently the additive that produced the best performing mix. The improvement was sufficiently large to suggest that a material generally less suitable for a bituminous mix (e.g., outwash sand and pit-run gravel) gains so much as to rival a more suitable material (e.g., crushed limestone). Lime-treated outwash sand and pit-run gravel had somewhat lower stabilities than crushed limestone, but they displayed greater resistance to cyclic exposure. Silane and indulin produced similar results but to a much lesser extent.

Pulse-velocity is a non-destructive test whose results appear related to modified Marshall stability values. In this study, there were remarkably similar rates of decline per cycle for pulse-velocity and Modified Marshall stability. This procedure was the only one which produced results with low erratic behavior in a reproducible manner. The pulse-velocity test appears to have great promise as a non-destructive test to monitor changes in stability of bituminous asphalt mixtures.
**TASK C - THE USE OF FOAMED ASPHALT FOR COLD MIXED RECYCLED BITUMINOUS PAVEMENT MIXTURES.**

**Introduction**

The determination of foaming characteristics of various asphalt cements obtained from different sources, was the first objective of this study.

The second objective was to evaluate the performance of three of these asphalts as binders for a recycled bituminous paving mix using the Gyratory and the Marshall compactive methods. The test procedures were performed using the Marshall stability test and the Hveem stabilometer.

The third objective was to investigate the effect of curing time and moisture on the stability of a recycled mix.

**Experimentation**

Three asphalts were selected from the study based upon their foaming characteristics. A foaming temperature of 325°F (160°C) and added water content of 2% were selected as the best conditions for optimum foam volume and half life of the foam. The performance of the three asphalts selected to be used as binders of recycled materials and artificially hardened mixtures was evaluated using Marshall and Hveem procedures. The
mixtures were compacted and evaluated by means of the gyratory compactor. The effects of water were determined by the water sensitivity test.

Conclusions

From the results of this study it can be stated that increasing the foaming temperature had the effect of increasing the expansion ratio and decreasing the half life of the foam. Therefore, a trade-off of half life for expansion ratio, or vice versa, is implicit in the selection of a particular set of values for foaming temperature and water content of the foamed asphalt to be produced.

The "fluff point" of the recycled material proved to be ideal for the mixing operation; however, in order to achieve useful compacted densities, it was necessary to evaporate some of this water.

It was observed that the Hveem Resistance values give the same optimum percent of foamed asphalt added as the Marshall stability values do. The Marshall stability values obtained by gyratory compaction were twice the values obtained by Marshall compaction. This was due to the greater densities obtained by means of the gyratory compactor.
The effect of seven day curing versus one day curing was quite pronounced for 0.5% and 1.0% of added binder.

Marshall stability values obtained following the water sensitivity test displayed a peak at 1% added binder. The effect of water in foamed asphalt-recycled mixtures decreased with an increase in binder content, and so does the percent water absorbed during the water sensitivity test.

Marshall stiffness values followed the same trends as those reported for Marshall stabilities with regard for both curing and moisture sensitivity. Finally, the differences in the stabilities of mixes using the three different asphalt bases were not great.

A test section utilizing foamed asphalt was identified and a research study was undertaken. The results from this study are presented in the Joint Highway Research Project Final Report No. 84-1, "Determination of the Structural Coefficients of a Foamed Asphalt Recycled Layer," authored by Mr. A. J. Van Wijk at Purdue University. Recommended structural coefficient values for foamed asphalt layers similar to those studied, were presented here. Finally, the feasibility of using foamed asphalt as a binder for cold-mix recycling projects was demonstrated by these research studies.
MAJOR FINDINGS

The major findings obtained from Task A were as follows:

- Outwash sand, crushed limestone and pit-run gravel can be successfully combined with foamed asphalt to produce a strong stabilized base course. To ensure satisfactory performance, the base course should be properly drained and sealed to prevent moisture infiltration.

- The foamed asphalt coating of these three aggregates was principally affected by the mixing water added during this process. A recommended range that included the "fluff point" of the aggregate material was found to be most suitable to promote the asphalt distribution and coating action.

- The effect of the initial moisture added on the amount of retained moisture after curing was more apparent at early curing stages (e.g., after one
day curing). The workability of the mixtures was also affected by this parameter.

- The foamed asphalt mixtures used in this task were suitable to be tested using the Resilient Modulus, Hveem Stabilometer and Marshall test procedures at room temperature. The tests performance of these foamed asphalt mixes was sensitive to temperature. Lower temperatures increased the resilient modulus, Hveem, and Marshall test values. On the other hand the effects of different mixing temperatures (50, 72 and 100°F), were insignificant.

- Curing time as well as test temperatures were the major controlling factors for the properties of these foamed asphalt mixtures. Pit-run gravel, outwash sand and crushed stone mix density and strength characteristics increased with curing time. A significant strength increase was obtained from 1 to 3 days air curing. Three day strengths were approximately the same as 7 day values in most cases. Satisfactory strengths were produced after an early curing period (1 day). All values obtained were well above normally specified minimums. This is an obvious advantage over emulsion and cutback treated mixtures which require a curing period of some length.
- The percent moisture retained in the mixture is a function of foamed asphalt content, added moisture and curing time. The curing time has a greater bearing on the amount of moisture retained, principally at high levels of foamed asphalt and mixing water contents.

- Dry densities and voids contents remained unaltered by curing. It is believed that they are a function of the amount of total fluids added to the mix as well as the compactive effort applied during the compaction process.

- Specimens subjected to the moisture sensitivity test after early curing (1 day) were difficult to test at any test temperature. Cracks developed during testing on the resilient modulus device. High foamed asphalt contents showed greatly improved strength values when compared with low contents for samples cured more than 1 day. Low bitumen contents and/or early cured specimens showed significant degradation in the moisture sensitivity test.

- The results of this part of the study support the conclusions found in the literature concerning the water sensitivity of foamed asphalt mixtures. The
test gives a better representation of the actual mix properties under adverse conditions. A minimum unsoaked strength as well as a minimum retained strength criterion should provide adequate control of the outwash sand, pit-run gravel, and crushed stone mix performance. The durability of these mixtures can be greatly enhanced by the use of additives, as can be seen in the following Task.

Task B, major conclusions for outwash sand, pit-run gravel, and crushed limestone foamed asphalt mixtures treated with three different additives and subjected to water saturation and freezing and thawing cycles:

- For outwash sand and pit-run gravel the additives enabled the foamed asphalt specimens to retain much more of their original stability after vacuum saturation than untreated specimens. Additives had little effect on crushed stone specimens in the water sensitivity test. The crushed stone is limestone and so the specimens were inherently resistant to water.
Durability was generally better with higher levels of asphalt in water sensitivity testing. Lime and silane additives resulted in better durability than would have been possible by the addition of more asphalt alone — the higher the level of additive, the better the resistance. Indulin improved durability better at lower levels of additive, but overall the effect was not large.

The additives enabled the foamed asphalt specimens to retain more of their original stability after repeated freezing and thawing than the untreated specimens.

The additives caused the foamed asphalt specimens to last longer under cyclic freezing and thawing than the untreated specimens.

Lime was consistently the additive that produced the best performing mix. The improvement in the Marshall stability numbers, stability retention, and specimen longevity are such that a material generally less suitable for bituminous mix such as outwash sand or pit-run gravel gains so much from the addition of lime as to rival a material more suitable for bituminous mix such as crushed limestone. The lime-treated outwash sand and pit-run
gravel specimens had somewhat lower stability than the lime-treated crushed limestone specimens, but they were able to withstand many more cycles of freezing and thawing before disintegrating.

- Silane and indulin appeared to yield favorable results for the foamed asphalt specimens in terms of stability retention and longevity; however, the results were not nearly so dramatic as for the lime-treated specimens.

- Pulse-velocity is a non-destructive test whose results appear to be related to the modified Marshall stability values obtained in this study. There are remarkably similar rates of decline per cycle for pulse-velocity and modified Marshall stability values. There also seems to be good reproducibility of pulse-velocity values among like specimens.

The major findings obtained from Task C were as follows:

- Not all asphalt cements are suitable for producing foamed asphalt. Anti-stripping agents and other additives may be added to asphalt cements to overcome the effects of silicone or chemicals that
reduce foaming capacity. Uniformity in terms of the same source (oil refinery), and grading of the binder material, are required in order to obtain homogeneous mixtures. Related ranges of foaming temperatures and amounts of water injected should be carefully studied prior to deciding the best combination of asphalt source, asphalt grade, and temperature as well as amount of foam water, for a specific type of foamed mixture. The grade of asphalt cement to be used depends on the type of pavement and the specific service conditions considered.

- For optimum foaming characteristics asphalt temperatures of about 325°F (150°C) to the maximum 375°F (190°C) for high viscosity grade asphalts. Half life and expansion ratio ranges are wide and difficult to predict due to the fact that these two parameters have interactive effects between each other, and with all the variables related with the asphalt cement itself. It can be stated that the most acceptable values of foam ratio and half life of the foam, are the ones obtained with the most economically available asphalt cement types and sources, for a determined type of work and location. Therefore, foam quality tests must be performed on available binder materials in
order to select the required temperature and foaming water rate that would yield the best combination of half life and expansion ratio values.

- Satisfactory laboratory procedures for comparing the foaming characteristics of asphalts commonly used in the State of Indiana as well as their uses in a recycled mix were established in this study.

- It was necessary to add small amounts of water to the recycled pavement material so that the foamed asphalt would thoroughly coat and adhere to it. The water content which gave the material its maximum loose volume, i.e., its "fluff point", proved to be an ideal water content for mixing purposes.

- It was necessary to dry the recycled mixes in a forced draft oven at 60°C (140°F) for 1 to 1 1/4 hours after mixing so that reasonable compacted densities could be achieved.

- The Marshall stability values obtained by Gyratory compaction were twice the values obtained by Marshall compaction.

- Maximum stability occurred at the least flow for the Gyratory compacted mixes. Maximum stability
and least flow did not coincide for the Marshall compacted mixes.

- Seventy-five blows of the Marshall hammer did not provide sufficient compaction to simulate initial compaction after construction. The possibility of achieving better results using a greater number of blows could be investigated.

- The effect of seven (7) day curing versus one (1) day curing was quite pronounced for 0.5% and 1.0% of added foamed asphalt binder.

- Marshall stability values obtained following the water sensitivity test displayed a peak at 1% added binder. The effect of water decreased with an increase in the binder content.

- Marshall Stiffness values followed the same trends as those reported for the Marshall Stabilities with regard to both curing and moisture sensitivity.

- The percent water absorbed during the water sensitivity test decreases with increasing percent binder added.
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- The Marshall Stability test results give the same optimum percent of asphalt added as the Hveem Resistance values.

- The Marshall Stiffness values tend to give a higher percent of asphalt to be added to the recycled mixture.
SUMMARY

Some major conclusions can be stated from this overall study on foamed asphalt mixtures:

- Foamed asphalt mixtures appear to require less amounts of binder than asphalt emulsion treated mixtures, to obtain similar stability and strength characteristics.

- Foamed asphalt is a useful and viable binder for stabilizing low quality aggregates that can be upgraded with lime in order to perform as a strong stabilized base course.

- High initial strength values obtained after short periods of curing are an advantage of foamed asphalt mixes when compared with asphalt emulsion or cutback treated aggregates that require longer curing periods.
- Pulse velocity test is a nondestructive test that correlates well with Marshall test results for monitoring the rate of degradation suffered by foamed asphalt mixtures subjected to water soaking and freezing and thawing cycles.
LABORATORY MIX DESIGN PROCEDURE
FOR FOAMED ASPHALT MIXTURES.
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Aggregates for Foamed Asphalt Cold Mixes.</td>
<td>33</td>
</tr>
<tr>
<td>2. Representative Data for Foamed Asphalt Mixtures.</td>
<td>34</td>
</tr>
<tr>
<td>3. Trial Asphalt Content</td>
<td>45</td>
</tr>
</tbody>
</table>

### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Water Flow as % of Weight of Asphalt Flow for Laboratory Foamix™ Asphalt Dispenser, Serial 77-03</td>
<td>36</td>
</tr>
<tr>
<td>2. Asphalt Weight vs. Delivery Time for Laboratory Foamix™ Asphalt Dispenser, Serial 77-03</td>
<td>39</td>
</tr>
</tbody>
</table>
LABORATORY MIX DESIGN PROCEDURE
FOR FOAMED ASPHALT MIXTURES

1. INTRODUCTION

The purpose of this report is to provide the reader with a step by step outline of the procedure that can be used to prepare and test laboratory foamed asphalt specimens. This procedure covers the selection, proportioning and testing components of foamed asphalt paving mixtures. Guidelines have been developed for this type of bituminous mix (see the References section of this report), however, no single procedure has been adopted yet as a standard procedure.

This recommended Laboratory Mix Design follows procedures developed within the Asphalt Institute, Mobil Oil of Australia, Ltd., CONOCO, and test methods developed by the California Division of Highways. The experience gained from studies performed at Purdue University using pavement materials available in the State of Indiana has also contributed for the development of this proposed manual.
2. AGGREGATE QUALITY EVALUATION

Thorough testing of the mineral aggregates is necessary in order to determine its suitability for use with foamed asphalt. Aggregate properties are important in the production of an optimum mixture. A wide range of materials are suitable for use with foamed asphalt including crushed stone, gravel, rock, sand, silty sand, sandy gravel, and recycled material.

2.1 Aggregate Test Methods.

The recommended test procedures used to evaluate aggregate properties are as follows:

* ASTM C-29, Test for Unit Weight of Aggregate (1)*F
* ASTM C-127 and ASTM C-128, Test for Specific Gravity and Absorption of Coarse and Fine Aggregate respectively (1)
* ASTM C:136, Test for Sieve or Screen Analysis of Fine and Coarse Aggregates (1)
* ASTM D-423, Test for Liquid Limit of Soils (2)
* ASTM D-424, Test for Plastic Limit and Plasticity Index of Soils (2)

* Note: Numbers in parentheses refer to the List of References of this report.
* ASTM D-698 or ASTM D-1557, Test for Moisture Density Relations of Soils, Using 5.5-lb Rammer and 12-in. Drop, or Using 10-lb Rammer and 18-in. Drop (2)

* ASTM D-2216, Laboratory Determination of Moisture Content of Soils (2)

* ASTM D-2487, Classification of Soils for Engineering Purposes (2)

2.2. Aggregate Gradation Requirements

Typical aggregate control values can be found in Table 2 of Reference No. 3 and in the Manual Series No. 19, Table 1, pg. 160-1; (The Asphalt Institute) for the recommended gradation of aggregates used in foamed asphalt cold mixes. A summary of such gradations is presented in this report as Table 1. The minimum of 5% passing sieve No. 50 and 3% passing sieve No. 200 is recommended together with alternate PI control of these fines. Higher amounts of fines are generally very desirable.

2.3. Aggregate Classification

A wide range of aggregates can be upgraded by foamed asphalt, as can be seen in Table 2. Characterization of the aggregate by the Unified Soil Classification System (2) is recommended as a guide to establish the suitability for its use with foamed asphalt. The Unified System considers the fine fractions of the
<table>
<thead>
<tr>
<th>Type of Agg:</th>
<th>Processed Dense-Graded Mixture</th>
<th>Semi-Processed Crusher, Pit or Bank Run</th>
<th>Sands</th>
<th>Silty Sands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve #</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 1/2&quot;</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>80-100</td>
</tr>
<tr>
<td>1&quot;</td>
<td>90-100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>60-80</td>
<td>90-100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>25-60</td>
<td>60-80</td>
<td>90-100</td>
<td>25-85</td>
</tr>
<tr>
<td>#4</td>
<td>25-45</td>
<td>35-65</td>
<td>60-80</td>
<td>75-100</td>
</tr>
<tr>
<td>#8</td>
<td>25-45</td>
<td>20-50</td>
<td>25-55</td>
<td>75-100</td>
</tr>
<tr>
<td>#50</td>
<td>5-18</td>
<td>5-20</td>
<td>35-65</td>
<td></td>
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<tr>
<td>#100</td>
<td>3-15</td>
<td>3-15</td>
<td>6-25</td>
<td></td>
</tr>
<tr>
<td>#200</td>
<td></td>
<td></td>
<td>3-15</td>
<td>15-65</td>
</tr>
</tbody>
</table>

Sand Equivalent, percent or Plasticity Index: 25 min. all gradations--or 15 max. all gradations--

EITHER CONTROL MAY BE APPLIED BUT NOT BOTH

Notes: 1. For certain purposes satisfactory results may be obtained with materials not conforming to these controls. Such use may be permitted based on field experience or laboratory studies.

2. Fines content and characteristics can have a significant effect upon foamed asphalt mixtures. Addition of some -200 mesh filter should be considered with materials containing minimum -200 mesh fractions. Where fines are classified as clayey, addition of a small percentage of lime may be advisable and economic.
TABLE 2. - REPRESENTATIVE DATA FOR FOAMED ASPHALT MIXTURES. (After Ref. No. 4)

<table>
<thead>
<tr>
<th>Soil Group Symbol D2487 Unified Classification</th>
<th>Suitability for use with Foam Asph.</th>
<th>Optimum Asphalt Range % Mass, mix</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW</td>
<td>Good</td>
<td>2.0-2.5</td>
<td>Permeable mixtures. Crushed fractions helpful.</td>
</tr>
<tr>
<td>GW-GC</td>
<td>Good</td>
<td>2.0-4.5</td>
<td>Permeable mixtures. Crushed fractions helpful.</td>
</tr>
<tr>
<td>GW-GM</td>
<td>Good</td>
<td>2.0-4.5</td>
<td>Permeable mixtures. Crushed fractions helpful.</td>
</tr>
<tr>
<td>GP-GC</td>
<td>Good</td>
<td>2.5-3.0</td>
<td>Low permeability. Crushed fractions helpful.</td>
</tr>
<tr>
<td>GC</td>
<td>Poor</td>
<td>4.0-6.0</td>
<td>Impermeable. Asphalt content critical. Crushed fractions helpful. Can be improved by added small percentage lime.</td>
</tr>
<tr>
<td>SW</td>
<td>Fair</td>
<td>4.0-5.0</td>
<td>Needs addition of -200 mesh filler.</td>
</tr>
<tr>
<td>SW-SM</td>
<td>Good</td>
<td>2.5-4.0</td>
<td>Needs more viscous asphalt and addition of -200 mesh filler.</td>
</tr>
<tr>
<td>SP-SM</td>
<td>Poor</td>
<td>3.0-4.5</td>
<td>May need addition of -200 mesh filler.</td>
</tr>
<tr>
<td>SP</td>
<td>Fair</td>
<td>2.5-5.0</td>
<td></td>
</tr>
<tr>
<td>SM</td>
<td>Good</td>
<td>2.5-4.5</td>
<td></td>
</tr>
<tr>
<td>SM-SC</td>
<td>Good</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>See Remarks</td>
<td>4.0-6.0</td>
<td>Alone-poor for foam. Needs small percentage of lime.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0-4.0</td>
<td>With lime - good for foam.</td>
</tr>
</tbody>
</table>

34
aggregate, which are critical to these mixes (4), as compared with the AASHTO system that does not.

Suitable amounts of mineral material separated into the different sieve sizes and dried, should be kept in storage. An approximate use of 1200 gr. of aggregate per sample should be considered.

3. **FOAMED ASPHALT EVALUATION**

The selection of the grade of the asphalt cement to be used will depend on type of pavement and the specific field service conditions, for the Foamix™ to be studied. Not all asphalt cements are suitable for producing foamed asphalt. Silicone and anti foam additives may reduce its foaming capacity (5). Uniformity in terms of source and grading of the binder material are also required in order to obtain homogeneous mixtures.

3.1 **Foamed Asphalt Production**

A laboratory foamed asphalt dispenser is required to apply replicate, precisely controlled volumes of foamed asphalt to a series of aggregate batches in simulation of field operations. A description of the operating instructions of the Laboratory Foamix™ Asphalt Dispenser developed by CONOCO (6) is summarized as follows:
FIGURE 1. - Water Flow as % of Weight of Asphalt Flow for Laboratory Foamix™ Asphalt Dispenser, Serial 77-03 (After CONOCO - Reference No. 6).
- Hot asphalt cement is circulated by a gear pump at a constant rate of about 0.5 gpm from a thermostatically controlled, heated 2 gallon storage tank.

- The asphalt cement contained in this tank should be preheated to at least 275°F (135°C) before the gear pump can be started. This operation takes from two to three hours with the heating system on.

- Another important component of this device is the foam nozzle that should be kept clean and well adjusted before each usage.

- Calibration of the water and air (pressure and flow), is obtained by a flowmeter. Figure 1 shows the different ratios of cc/min of water by weight of foamed asphalt delivered. This calibration should be performed with both, the water and the air switches on.

- The desired amount of foamed asphalt to be added to a test batch of aggregate can be obtained from the chart presented in Figure 2. This figure presents the weight of foamed asphalt produced (in grams) at various delivery times (in seconds).
series of timers on the panel table control this automated operation. The slope of the curve shown in this graph is of 36.4 gr./sec. A correction factor for different specific gravity asphalt cements must be applied as follows:

\[
AC_{New}(gr.) = \frac{\text{Chart grs.} \times \text{Sp. Gr.}_{New}}{1.036}
\]

3.2. Foamed Asphalt Quality Test

Foamed asphalt samples are produced in containers of approximately one gallon (3.8 liters) capacity, to verify foamability of the asphalt cement. It is also necessary to establish operating levels for asphalt temperature and the rate of addition of foaming water. Foam quality evaluation for several combinations of asphalt source, grades, temperatures, and amounts of foam water, are reported in Reference No. 7.

Operating levels should be selected, that will yield foamed asphalt whose maximum volume is at least ten times that of the asphalt before foaming (expansion or volume ratio), and a foam which will be sufficiently stable that its half life (the time in seconds for the maximum volume of the foam to be reduced by 50%) will be 25 or more seconds.
FIGURE 2. - Asphalt Weight vs. Delivery Time for Laboratory Foamix™ Asphalt Dispenser, Serial 77-03
(After CONOCO — Reference No. 6).
Asphalt temperatures of about 325°F (160°C) are used for high viscosity grade asphalts.

A water addition rate of about 2% volume on asphalt volume is typical for foaming but may vary from 1 to 3% volume (refer to Figure 1).

Half life and expansion ratio of the foam are wide and difficult to predict. The most acceptable values of these parameters are the ones obtained with the most economically available asphalt cement types and sources for a determined project and location. Therefore, foam quality tests must be performed on available binder materials, in order to select the required temperature and foaming water rate that would yield the best combination of half life and expansion ratio values for these binders. The related literature \(3,4,5,7,8\) indicates ranges for expansion ratio between 6 and 20, and half life of 10 to 80 seconds.

3.3. Asphalt Cement Characteristics

Test parameters such as specific gravity, viscosity, etc. are required in order to characterize the properties of the asphalt cement to be used in the stabilization process. These characteristics are useful for the determination of the air voids and other important mix parameters. Typical standard test procedures are as follows:
* ASTM D-5, Test for Penetration of Bituminous Materials (9)

* ASTM D-36, Test for Softening Point of Bitumen (Ring and Ball Apparatus) (9)

* ASTM D-170, Test for Specific Gravity of Semi-Solid Bituminous Materials (9)

* ASTM D-113, Test for Ductility of Bituminous Materials (9)

* ASTM D-1856, Test for Recovery of Asphalt from Solution by Abson Method (9)

* ASTM D-2170, Test for Kinematic Viscosity of Asphalt (Bitumens) (9)

4. SELECTION OF MIX PROPORTIONS

The amounts and proportioning of the different components of foamed asphalt mixture should be initially determined based on trial mixes. Recommended optimum foamed asphalt content values are listed in Table 2. Workability and strength results of the Foamix, as well as visual inspection during mixing and compaction, should be performed before selecting the
final levels of mixing water and binder contents to be used in the samples.

4.1 Aggregates

Considerations of the maximum size of the aggregate must be taken in preparing the mixes. Usually, mechanical laboratory mixers are of small capacity and plus No. 4 sieve particles tend to lock or block the blade. All the test aggregate batch can be directly mixed with the foamed asphalt, or it can be separated into plus and minus No. 4 sieve sizes without significantly affecting the properties of the final mix. However, every effort should be made to add the foamed asphalt to the whole batch of inert material.

4.2 Mixing Water Content

Mixing water is used in cold mixtures to aid the dispersion of the binder in the aggregate mass. Too much initial water will affect the compaction of the mixture, while too little moisture will create lumps of asphalt and fines.

4.2.a Optimum Moisture Content (OMC)

The optimum moisture content of each different type of aggregate should be determined by ASTM D-698 or ASTM D-15557 (2) as mentioned in Section 2.1 of this report. This quantity of moisture represents the
desired amount of total fluid content required to achieve the optimum compaction of the mix. ("Total fluid content" is the mixing water plus the foamed asphalt of the mix.) Trial mixes should be made to evaluate the density and stability of Fomix prepared at different levels of fluid content such as lower and greater amounts of the OMC from the aggregate being used.

4.2.b Fluff Point Moisture Content

The review of the literature shows that among others, optimum mixing conditions for cold mixes occur when the aggregate is brought to its maximum volume consistent with easy manipulation (8). Standard procedures for this purpose are not reported, however, the methodology described below has proven to be accurate enough for this purpose (8).

A graduated cylinder or beaker, a spatula, a mixing vessel and a balance are used to measure the volume of 300 gr. to 500 gr. of the fraction of aggregate being mixed with the foamed asphalt.

This sample is thoroughly mixed with one percent of water (by weight of dry aggregate) in the mixing vessel and loosely poured into the graduated beaker. The difference in volume (increasing values) after this operation is recorded. Additional one percent
Increments of water are added to the aggregate, mixed and loosely poured into the graduated beaker until the loose volume of the damp aggregate versus the moisture content curve has been properly established and a volume decrease has been noted. The amount of water needed to obtain this maximum volume of loose material, in terms of percent by total weight of dry aggregate, is reported as being the "fluff point" moisture content of the aggregate being analyzed. The required moisture is generally on the "dry" side of the OMC curve of the aggregate. This amount of moisture can be used to prepare trial mixes with recommended values of binder content.

4.3. Foamed Asphalt Content

The selection of optimum moisture and asphalt contents, for mixing and compaction purposes, should be based initially on maximum densities and stabilities achieved for three or more trial mixes. The amounts of binder content can be selected from tables and recommended ranges presented by CONOCO (3) and the Asphalt Institute (10) among others.

Table 2 and Table 3 (reported next), list values for foamed asphalt contents that can be used initially. These trial binder contents are based on the type of aggregate being used, namely, the percent of fines present in the material.
<table>
<thead>
<tr>
<th>Aggregate Wet Gradation Analysis</th>
<th>Pass No. 200 US Screen</th>
<th>Foamed Asphalt Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Minus 0.075mm), % Mass</td>
<td>% Mass on Dry Aggregate</td>
</tr>
<tr>
<td>Less than 50</td>
<td>3.0 to 5.0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>5.0 to 7.5</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>7.5 to 10.0</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Above 10.0</td>
<td>4.5</td>
</tr>
<tr>
<td>More than 50</td>
<td>3.0 to 5.0</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>5.0 to 7.5</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>7.5 to 10.0</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>Above 10.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Mixtures made with a trial foamed asphalt content should be prepared with three levels of moisture content, in a range of 1.5 to 2.0 percent less than the "fluff point" of the aggregate being used, to a maximum of 1.5 to 2.0 percent more than this value. Moisture levels somewhere between 40 to 80% of the aggregate OMC are also recommended (3).

Test results from these mixtures (stability, density, etc.), will indicate the optimum percentage of mixing water to be used. With this optimum amount of initial moisture, two additional levels of binder content should be evaluated by means of test procedures described in Section 6 of this report. Visual inspection for optimum dispersion of the binder during mixing and for best compaction conditions will help to establish proper levels of mixing water and initial moisture contents.

Finally, a moisture sensitivity test is definitely needed in the mix design to indicate the limitations of foamed asphalt mixes to water damage. The method recommended in a laboratory report of the Asphalt Institute (11) as modified in Reference No. 8, can be used (this modified test procedure is described in more detail in Section 6 of this report). The objective of this early evaluation of the Foamix is to determine the lower level of asphalt content at which the mixture
will withstand the effects of water without crumbling or being severely damaged. The required amount of foamed asphalt for this purpose is generally between 1 to 2% higher than the optimum binder content for maximum stability of the mix.

These values of binder and mixing water contents should be adjusted until test results of trial mixes (e.g., Marshall stability, density, etc.) show the best combinations of fluids to be used in the preparation of the samples.

5. SPECIMEN PREPARATION AND HANDLING

5.1. Mixing.

When the aggregate maximum size is 3/8 in. or more, aggregate test batches may be separated into plus No. 4 and minus No. 4 sieve fractions. Apply foamed asphalt to the minus No. 4 sieve fraction of batch at the desired moisture level and mix for about 2 to 2 1/2 minutes in a mechanical mixer. Add plus No. 4 sieve portion of batch (premoistened with fine moist spray) to mixed part, and complete mixing by hand with spoon for 30 seconds. Immediate compaction of the mixture should follow to avoid loss of the required moisture for compaction purposes. However, as mentioned before, every effort should be made to add the binder to the whole batch of aggregate.
The total batch weight, including bitumen, should be that necessary to produce a specimen 4 in. in diameter and 2.5 ± 0.1 in. height. Typical amounts of 1100 gr. to 1200 gr. total mix are satisfactory for this purpose.

5.2. **Compaction**

After a thorough mixing of the different proportions of aggregate, mixing water and foamed asphalt (see Section 4.1 of this report), the compaction of the batch of mixture is next. For this purpose, the Hveem kneading compactor or the gyratory machine can be used. Marshall compaction appears to give the weakest (less dense) samples of the two compaction methods mentioned (7,8).

The final compactive effort of 500 psi (3.45 MPa) is recommended for the kneading compactor, and a compactive effort of 40 revolutions at 200 psi (1.38 MPa) is believed to be appropriate when using the gyratory machine in accordance with ASTM D-3387-74T.

5.3. **Curing**

The criteria for the curing of the Foamix specimens should be first, to leave the sample in the mold at room temperature for 24 hours before extrusion. The representative properties of the mix should be tested
and obtained at various stages and conditions as submitted by traffic and environment when in service. For this purpose, two curing conditions are recommended.

The "early curing" condition or 24 hours in the mold at room temperature that will represent the initial gaining of strength of the mixture while in the field. This analysis is for practical consideration of hauling traffic and construction purposes.

The "long term" curing condition appears to be achieved after seven days of curing the sample out of the mold, at room conditions. The same effect is obtained by leaving the extruded specimen in the oven at 104°F (40°C) for 24 hours. It is believed that 90% or more of the mixture final strength is achieved this way.

6. RECOMMENDED TEST PROCEDURES

This section is a brief description of the recommended test procedures used for the evaluation of laboratory Foamix samples. Before any test is performed, the sample must be already mixed, compacted and cured (refer to Section 5 of this report).
6.1. Density of Compacted Specimens

For this purpose, two procedures can be followed:

- First, the bulk specific gravity of the sample can be obtained by the Saturated Dry Method, ASTM D-2726; however, since foamed asphalt mixtures have higher air voids content than normal hot mix materials, the absorption of moisture during this process is significant. This moisture weakened the specimen distorting further test results. For this reason it is recommended to use samples made for this purpose, disposing them after the test is performed.

- A second and more convenient way to obtain the density or unit weight of the laboratory Foamix samples is as follows:

  After the samples are cured, their weights in air and their heights are measured and recorded. The weights with a precision of ± 0.5 gr. and the heights, up to ± 0.05 cm (± 0.02 in). The volume and the unit weight of the specimens are calculated without damaging the sample by water saturation. Later testing can be performed on the same specimen.
6.2 Resilient Modulus Test

A dynamic test frequently used to determine the resilient characteristic of a pavement material is the method of diametral loading. The diametral compression test is preferred over other modes of repeated load applications, because it is simple to run and requires Marshall or Hveem size specimens. The test is conducted by applying a light pulsating load across the vertical diameter of the sample and recording the vertical deformation experienced by the specimen during this load application. Description of the equipment used and the detailed test procedure can be found in Reference No. 8. Theoretically, the resilient modulus test (\(M_R\)) is a non-destructive type of test. This means that specimens can be submitted to other test procedures after the \(M_R\) test has been performed. However, appropriate judgment will determine if this test sequence can be followed. Early cured and water saturated samples sometimes are too weak to resist the pulsating load application of the \(M_R\) test and large deformations and/or cracks start to develop. In this case, further testing of the sample will give misleading results.
6.3. **Hveem Stabilometer Test**

The Hveem Stabilometer is a common test procedure used in the characterization of asphalt mixtures. The modified procedure of the Hveem test is recommended, namely, to determine the R and S values at room temperature rather than at 140°F and (60°C) as required in the ASTM standards.

The Hveem resistance (R-value) test has been standardized by ASTM Designation D-2844, "Resistance R-value and Expansion Pressure of Compacted Soils" (9). The conventional Hveem stability (S-value) test is standardized by ASTM Designation D-1560, "Resistance to Deformation and Cohesion of Bituminous Mixtures by means of Hveem Apparatus" (9).

Another practical modification of the standard procedures is to obtain both parameters from the same test run. Studies on cold mixes show that the value $D_2$, the displacement value used in the calculation for both the R-value and S-value did not change at repeated testing. $D_2$ is a function mainly of the surface texture of the specimen (8). It is thus appropriate to test a specimen in the stabilometer up to a load of 6000 lb (26.69 kN) according to the standard Hveem stabilometer test procedure and to calculate the R-value as well as the S-value from the recorded lateral pressures.
6.4 **Marshall Test Procedure**

As mentioned previously, this test is performed on samples already evaluated in the Hveem stabilometer and/or the M<sub>R</sub> apparatus. It is expected to determine trends and patterns of the Foamix properties with the Marshall test results. **Marshall stabilities and flow results obtained this way should not be used for correlation with accepted Marshall values listed in the literature for virgin Foamix samples.**

6.5 **Water Sensitivity Test**

This test procedure is used to measure the resistance of the foamed asphalt mix to water.

After compaction, the sample is left 24 hours in the mold to cure at room conditions. After this initial period, it is extruded and cured for 24 hours more at 104°C (40°C). Finally, the specimen is allowed to cool to room temperature and its weight in air and its height are recorded. The specimen then is placed in a bell jar, covered with distilled water (1/2 in over the top surface of the sample) and a vacuum of 100 mm Hg is applied for 1 hour. At the end of this period, the vacuum is released and the sample is left submerged in water for another hour before testing. The weight in air is again determined and the differences with the original weight is the amount of moisture absorbed by
the Foamix during the water saturation test. $M_R$, Hveem and Marshall values should be obtained on the treated samples.

6.6 Other Recommended Test Parameters

More information can be obtained from the laboratory Foamix samples when a sequence of testing is carefully planned and adopted early in the study. The following is a sequence of testing procedures adopted in Reference No. 8, that include some other parameters than the ones listed before.

- The determination of the moisture lost during the curing period to which the specimen is subjected, is a useful parameter to evaluate the rate of curing of the Foamix while in the field.

- The unit weight at time of testing as well as the dry density of the compacted mix can be used to determine the degree of compaction achieved under the different proportions of materials used.

- The air voids content of the sample will help to indicate the degree of permeability of the mix for water damage purposes: the higher the voids content, the larger the distress that will occur by the action of water.
- The resilient modulus, Hveem stabilometer and Marshall test should be performed in "dry" and water saturated samples to evaluate the degree of reduction in strength and other mix properties due to water effects.

It is expected that the determination of the optimum mix proportions, materials and conditions, can be determined from these test results. $M_R$, Hveem Marshall, density, etc. results, may have a peak value at different moisture and/or foamed asphalt content. Good judgement and a careful evaluation of early test results will help to set a final group of mix variables to be used throughout the laboratory study. The following of the different steps of this proposed "Mix Design Procedure" will be sufficient to evaluate compacted foamed asphalt mixtures.
6. REFERENCES FOR DESIGN PROCEDURE MANUAL


PART II

DURABILITY CHARACTERISTICS OF FOAMED ASPHALT MIXTURES
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pit-run gravel gradation</td>
<td>78</td>
</tr>
<tr>
<td>2. Pit-run gravel properties</td>
<td>78</td>
</tr>
<tr>
<td>3. Outwash sand gradation</td>
<td>81</td>
</tr>
<tr>
<td>4. Outwash sand properties</td>
<td>81</td>
</tr>
<tr>
<td>5. Crushed stone gradation</td>
<td>83</td>
</tr>
<tr>
<td>6. Crushed stone properties</td>
<td>83</td>
</tr>
<tr>
<td>7. Silane properties</td>
<td>85</td>
</tr>
<tr>
<td>8. Calcium hydroxide lot analysis</td>
<td>88</td>
</tr>
<tr>
<td>9. Indulin properties</td>
<td>90</td>
</tr>
<tr>
<td>10. AC-20 properties</td>
<td>93</td>
</tr>
</tbody>
</table>

## Appendix

Table

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1. Water sensitivity data</td>
<td>183</td>
</tr>
<tr>
<td>B1. Freeze-thaw data</td>
<td>202</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Water sensitivity design matrix</td>
<td>75</td>
</tr>
<tr>
<td>2.</td>
<td>Freeze-thaw design matrix</td>
<td>76</td>
</tr>
<tr>
<td>3.</td>
<td>Laboratory Foamix tm Asphalt Dispenser</td>
<td>96</td>
</tr>
<tr>
<td>4.</td>
<td>California kneading compactor</td>
<td>100</td>
</tr>
<tr>
<td>5.</td>
<td>Riehle compression machine</td>
<td>102</td>
</tr>
<tr>
<td>6.</td>
<td>Vacuum saturation equipment</td>
<td>106</td>
</tr>
<tr>
<td>7.</td>
<td>Pulse-velocity equipment</td>
<td>108</td>
</tr>
<tr>
<td>8.</td>
<td>Resilient modulus equipment</td>
<td>110</td>
</tr>
<tr>
<td>9.</td>
<td>Marshall testing equipment</td>
<td>113</td>
</tr>
<tr>
<td>10.</td>
<td>Water sensitivity and control modified Marshall stability values for pit-run</td>
<td>147</td>
</tr>
<tr>
<td></td>
<td>gravel specimens with 4.00% foamed asphalt content</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Modified Marshall stability values versus number of freeze-thaw cycles for</td>
<td>152</td>
</tr>
<tr>
<td></td>
<td>pit-run gravel specimens</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>Modified Marshall stability values versus number of freeze-thaw cycles for</td>
<td>153</td>
</tr>
<tr>
<td></td>
<td>outwash sand specimens</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>Modified Marshall stability values versus number of freeze-thaw cycles for</td>
<td>154</td>
</tr>
<tr>
<td></td>
<td>crushed stone specimens</td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>Longevity graph -- number of freeze-thaw cycles a specimen survives before</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td>disintegrating</td>
<td></td>
</tr>
</tbody>
</table>
15. Pulse-velocity-modified Marshall stability comparison. . . . . . . . . . . . . . 158
16. Pulse-velocity reproducibility. . . . . . . 159
Highlight Summary

Foamed asphalt offers several benefits for use as a stabilization agent: (1) slightly lesser amounts of asphalt are required; (2) there is less release of hydrocarbons; (3) it is less expensive once a foamer is available. The mixes, however, appear to have larger void content. Experiences in mix design in the associated tasks of this project indicate a larger water sensitivity is present. This report, representing the work of Task B of the parent project, deals with an examination of the durability characteristics of several foamed asphalt mixes.

Two types of durability were examined: (1) the effect of soaking in water; (2) the effect of cycles of soaking in water, freezing, and thawing. Three aggregates were used: (1) outwash sand; (2) pit-run gravel; (3) crushed limestone. Asphalt contents were those for "at-optimum" condition and 1 percent above "optimum". Three additives were examined to see if they would improve the durability behavior: (1) lime; (2) indulin; (3) silane.
The effects of water and of cyclic freezing and thawing were monitored by several tests: (1) change in weight; (2) modified Marshall stability (at 72° F); (3) pulse-velocity; (4) resilient modulus.

Vacuum saturation (water sensitivity test) weakened all the specimens. The additives enabled the pit-run gravel and outwash sand to retain much more of their original stability, while they had little effect on the crushed stone. Higher levels of asphalt content appeared to create slightly better water sensitivity behavior. Lime and silane additives resulted in better water durability than would have been possible by the addition of more asphalt alone.

Cyclic freezing and thawing also weakened all the specimens. Additives enabled the specimens to retain more of their original stability than did the untreated specimens. The additives also appeared to create a larger cyclic longevity. Lime was consistently the additive that produced the best performing mix. The improvement was sufficiently large to suggest that a material generally less suitable for a bituminous mix (e.g., outwash sand and pit-run gravel) gains so much as to rival a material more suitable for a bituminous mix (e.g. crushed limestone). Lime-treated outwash sand and pit-run gravel had somewhat lower stabilities than crushed stone, but they displayed larger
resistance to exposure. Silane and indulin produced similar results but to a much lesser extent.

Pulse-velocity is a non-destructive test whose results appear related to modified Marshall stability values. In this study, there were remarkably similar rates of decline per cycle for pulse velocity and modified Marshall stability. This procedure was the only one which produced results with low erratic behavior in a reproducible manner. The pulse velocity test appears to have great promise as a non-destructive test to monitor changes in stability.
CHAPTER 1
INTRODUCTION

There is no question that an integral part of today’s transportation system is the highway. Man is constantly striving to improve his highways in order to make that part of his transportation system more efficient. However, with an increasing awareness of the environment, several constraints have been placed on the avenues man can choose when seeking to further improve his highways. These constraints include: (a) the limited amount of natural resources; (b) the level of acceptable pollution which is unavoidably created by the use of certain resources; and (c) man’s limited budget which must deal with the ever-increasing financial cost of certain resources.

Consequently, traditional methods of improving highways are undergoing change to better meet the constraints listed above. One of these traditional methods is the stabilization of aggregates with bituminous materials.
Bituminous materials used for highway paving are largely a by-product of petroleum refining. Petroleum is a limited resource, a fact which has become more apparent in recent years. Certain methods of paving with bituminous materials cause higher levels of hydrocarbons to be released into the environment than other methods (i.e., using cutback or emulsified asphalts vs. asphalt cements). The increasing scarcity of petroleum as a natural resource and tighter environmental controls cause the cost of bituminous materials to continually increase. Other expenses include the heating of aggregates and bitumen for hot mix applications, the transportation of large amounts of water for emulsified applications, and the amount of time (which is money) needed for aeration of emulsified and cutback applications (3).

More attention as of late has been given to a material known as foamed asphalt. Foamed asphalt falls within the limits of the aforementioned constraints better than other bituminous materials for a number of reasons.

First, a slightly lesser amount of asphalt is generally needed for foaming than in other kinds of asphalt applications. The foamed asphalt is sprayed onto the cold, wet aggregates and coats the aggregates better than if the asphalt were not foamed. To get the
same amount of coverage as the foamed asphalt with "unfoamed" asphalt, either the aggregates would need to be hot and dry, or else more asphalt would be necessary.

Second, there is not the same level of hydrocarbon pollutant release when paving with a foamed asphalt mix as there is when paving with cutback or emulsified asphalt mixes (notably during the aeration period for the cutback or emulsified asphalts -- in fact, there is generally no need for an aeration period with foamed asphalt). The asphalt is foamed by virtue of an injection of 1 to 2 percent cold water into hot (approximately 350°F) asphalt. The foamed mix is stable upon compaction and does not need to cure or "break."

Third, the foamed asphalt process is less expensive once a foamed asphalt generator has been made available. The aggregate is used in a cold, wet condition and thus requires no heating or drying. As indicated before, there is no aeration period, so weather plays a lesser role during field compaction. Foamed asphalt-aggregate mix has even been stockpiled for up to a year before placement and compaction, so there is less waste (11).

Durability of foamed asphalt mixtures has been questioned. The concern is due to foamed asphalt mix-
tures having lower bitumen contents and higher voids content than are generally found in standard asphalt mixes (1). This study will address the durability question. Two types of durability will be investigated — the effect of soaking in water, and the effect of cycles of soaking in water, freezing, and thawing, on the stability of foamed asphalt specimens. Control specimens, i.e., specimens which have not been subjected to soaking or freezing and thawing, will also be made and measured for stability.

Three different aggregate types will be used — outwash sand, pit-run gravel, and crushed stone.

A common problem limiting the durability of asphaltic concrete is that of the asphalt being stripped from the aggregate by water. Certain chemicals have been found to increase the bonding power of asphalt to aggregates (23). Three additives will be utilized in this study to determine if they have any effect on the durability of foamed asphalt specimens. Also, a series of specimens without any additives will be used as a control. The additives to be used in this study are calcium hydroxide (a.k.a. "lime"), Silane, and Indulin. Lime has been used successfully as an additive to asphaltic concrete in the past (23). In this study the lime will be added in slurry form to the fine aggregate. Silane, the name of a family of
organic chemicals, has recently been used as an additive to asphaltic concrete specimens. Silane has been recommended as a possible anti-stripping agent (14). It can either be added directly to the asphalt or used as an aggregate pretreatment. In this study the Silane will be added to the water used to bring the aggregate to the specified moisture content. Indulin, typical of several liquids which are marketed as anti-stripping agents, will also be used in this study. It will be added directly to the asphalt before the asphalt is foamed.

Several tests will be run to monitor the effect of water and cyclic freeze-thaw on the strength of the foamed asphalt mix specimens. These tests include: resilient modulus, a modified Marshall method, pulse-velocity, and weight measurements. The results of the "non-destructive" tests -- resilient modulus, pulse-velocity, and weight measurements -- will be compared to a modified version of the more common (but destructive) Marshall stability test. The purpose of the comparison is to establish the likelihood of a correlation between the modified Marshall method and a non-destructive test. Such a correlation might then be used as a gage of relative deterioration of a foamed asphalt specimen subjected to cycles of water soaking, freezing, and thawing.
At the time the research proposal was formulated it was the expectation of the investigators that it would be possible to use Hveem stability values as a means of monitoring the effects of the exposure conditions on the various mixtures. However, when the exposure tests were started it became evident that volume changes, experienced by the specimens as a result of the exposure tests, would make it impossible to use the Hveem cell as a means of determining the effects of the exposure conditions. In order to obtain a strength measure for the effects of the exposure it was decided to fall back on the modified Marshall Test.

With the foregoing, it is hoped that the durability behavior of foamed asphalt mixes will be better understood so that these mixes can be seriously considered for field use.
CHAPTER 2
REVIEW OF LITERATURE

Foamed asphalt was developed in the 1950’s by Professor Csanyi of Iowa State University. The purpose for foaming the asphalt was to lower the viscosity and increase the volume of the asphalt so that there would be better dispersion of the asphalt on cold, wet aggregate. Prior to the development of the foaming process, the best way to disperse asphalt on cold, wet aggregate was by using cutback solvents or emulsions. Foamed asphalt does not require solvents or emulsions, so the environmental and financial drawbacks associated with cutback and emulsified asphalts are eliminated. As a result, interest in foamed asphalt has grown recently. The disadvantages of cutback and emulsified asphalts and the advantages of foamed asphalt are discussed in greater detail in the Introduction section.

Comparatively little research has been done on foamed asphalt because of its suspected lack of durability after saturation and freeze-thaw cycles (28).
Previous attempts to address the durability question have been discouraging. Foamed asphalt specimens subjected to various types of saturation and freezing and thawing have often fallen apart or been too damaged to test afterwards (2,9,22,28).

A series of studies was proposed for research at Purdue University to further expand the knowledge of foamed asphalt characteristics. The topics included: (a) creating a foamed asphalt mix design procedure; (b) evaluation of the durability characteristics of foamed asphalt mixtures; (c) using foamed asphalt for cold mix recycled bituminous pavement mixtures; and (d) a field investigation with a test section of foamed asphalt pavement. The first topic was covered by Shofstall (28) and Castedo (9). The third topic was covered by Tia (29). This study concerns the topic of durability. The field investigation has yet to be conducted.

Both Shofstall and Castedo attempted some water sensitivity testing, but for the most part encountered the same problem as previous investigators -- namely, the test was too harsh. As a consequence it was recommended that a less severe durability testing program be adopted for this experiment. Originally, two additives had been included in the durability section; a third one was added to this section of the research in view of the poor performance exhibited by untreated
specimens in water sensitivity as seen by Shofstall and Castedo.

A new procedure for curing foamed asphalt specimens and testing for water sensitivity was recommended by Ruckel, Acott, and Bowering (26). For a simulated 7-day dry field cure ("intermediate cure"), they specified the specimens be cured in the mold on their sides at room temperature for 24 hours, followed by extrusion and 24-hour cure in an 104°F (40°C) oven. After cooling to room temperature, specimens would be ready for testing.

The water sensitivity test entailed taking these cooled specimens (after weighing) and placing them in a container capable of holding a vacuum, covering them with room-temperature water 1/2" above their top surface, sealing the container and starting a vacuum. One hundred mm of Hg vacuum were to be applied for one hour. Then the vacuum was to be slowly released, and the specimens allowed to continue soaking for another hour. The specimens were removed from the water at this time and weighed in the saturated-surface-dry condition. This constitutes their water sensitivity test.

Ruckel, Acott, and Bowering's intermediate cure and water sensitivity test procedures were used in this experiment. This same water sensitivity procedure was
used for the freeze-thaw section as well. After each period of thaw, the specimens were vacuum saturated before being frozen again.

It would appear that the only thing limiting more widespread use of foamed asphalt mixtures is its questionable durability and the resultant lesser strength. This research will investigate the durability characteristics of foamed asphalt specimens through experimentation. Additives will be employed to see if they can increase the specimens' resistance to deterioration.
CHAPTER 3
MATERIALS AND EQUIPMENT

A design matrix for the water sensitivity testing is shown in Figure 1. A design matrix for the freeze-thaw testing is shown in Figure 2. The various aspects of these design matrices will be discussed in the sections to follow.

3.1 Aggregate

Three different types of aggregate were used in this research. They were an outwash sand, pit-run gravel, and crushed stone. Three aggregates were used because there was some suspicion "that the characteristics of foamed asphalt will allow successful use of a broader spectrum of aggregate and soil materials as stabilized bases and subbases" (3). Also, any universal effect from the additives included in this study could be verified by more than one occurrence by comparing the results of the three aggregates.
<table>
<thead>
<tr>
<th>TEST AGGREGATE</th>
<th>ADDITIVE FOAMED ASPHALT CONTENT</th>
<th>WATER CONTENT</th>
<th>CONTROL</th>
<th>WATER SENSITIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit-run Gravel</td>
<td>None</td>
<td>3.9%</td>
<td>3 3 3 3</td>
<td>3 3 3 3</td>
</tr>
<tr>
<td></td>
<td>Silane</td>
<td>0.002% 0.005% 1.0% 2.0%</td>
<td>A B A B A B A B A B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indulin</td>
<td>0.3% 0.6%</td>
<td>A B A B A B</td>
<td></td>
</tr>
<tr>
<td>Outwash Sand</td>
<td>None</td>
<td>6.0%</td>
<td>3 3 3 3</td>
<td>3 3 3 3</td>
</tr>
<tr>
<td></td>
<td>Silane</td>
<td>0.002% 0.005% 1.0% 2.0%</td>
<td>A B A B A B A B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indulin</td>
<td>0.3% 0.6%</td>
<td>A B A B A B</td>
<td></td>
</tr>
<tr>
<td>Crushed Stone</td>
<td>None</td>
<td>4.0%</td>
<td>3 3 3 3</td>
<td>3 3 3 3</td>
</tr>
<tr>
<td></td>
<td>Silane</td>
<td>0.002% 0.005% 1.0% 2.0%</td>
<td>A B A B A B A B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indulin</td>
<td>0.3% 0.6%</td>
<td>A B A B A B</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 1. WATER SENSITIVITY DESIGN MATRIX**
**Figure 2. Freeze-Thaw Design Matrix**

<table>
<thead>
<tr>
<th>Aggregate Type</th>
<th>Control</th>
<th>Freeze-Thaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit-Run Gravel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A: 4.00%</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Water Content: 3.9%</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Outwash Sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A: 4.25%</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Water Content: 6.0%</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Crushed Stone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A: 4.50%</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Water Content: 4.0%</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
3.1.1 **Pit-run Gravel**

The first of the three aggregates used in this study is known as a pit-run gravel. The determination of the specific gradation to be used, the source, and properties of the aggregate were accomplished in earlier studies at Purdue University \((9, 16, 21, 27, 28)\).

The pit-run gravel material was obtained from the Western Materials Company, a division of the Medina Aggregate Company, located in West Lafayette, Indiana. The quarry is listed as source No. 2132 by the Indiana State Highway Commission.

The material is a terrace sand and gravel that was deposited by the Wabash River. The aggregate consists of roughly two-thirds weathered limestone and dolomite (carbonate) and one-third noncarbonates. Up to one-fifth of the noncarbonates consist of various types of coarse-grade igneous rocks. The material has been dry-sieved and stored in containers at room temperature in the Bituminous Laboratory, Grissom Hall, Purdue University. The proper gradation can then always be met by weighing the necessary amount from each container \((9, 16, 21, 27, 28)\).

The gradation used for the pit-run gravel is given in Table 1. The properties of pit-run gravel are listed in Table 2.
Table 1. Pit-run gravel gradation.

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Percent Passing</th>
<th>Percent Retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&quot;</td>
<td>100.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>90.0</td>
<td>10.0</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>84.0</td>
<td>6.0</td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>76.0</td>
<td>8.0</td>
</tr>
<tr>
<td>#4</td>
<td>65.0</td>
<td>11.0</td>
</tr>
<tr>
<td>#8</td>
<td>50.0</td>
<td>15.0</td>
</tr>
<tr>
<td>#16</td>
<td>35.0</td>
<td>15.0</td>
</tr>
<tr>
<td>#30</td>
<td>20.0</td>
<td>15.0</td>
</tr>
<tr>
<td>#50</td>
<td>8.0</td>
<td>12.0</td>
</tr>
<tr>
<td>#100</td>
<td>5.0</td>
<td>3.0</td>
</tr>
<tr>
<td>#200</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>pan</td>
<td>0.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 2. Pit-run gravel properties.

- **Bulk Specific Gravity (SSD)**: 2.644 (ASTM C 127)
- **Apparent Specific Gravity**: 2.710 (ASTM C 127)
- **Absorption**: 1.56% (ASTM C 127)
- **Mineral Filler (< #200 sieve) non-plastic**: (ASTM D 424)
The aggregate must be in a moist condition before the foamed asphalt is added. Otherwise, the bituminous material will not be thoroughly incorporated. Each aggregate gradation has a range of water contents at which optimum mixing conditions occur. This is commonly known as the "fluff point" (18). The fluff point is on the dry side of a material's optimum moisture content. The fluff point is the water content at which the aggregate reaches its maximum volume when loosely poured into a container (9). Fluff points for all three aggregates used in this study were determined in earlier research at Purdue University. The fluff point for pit-run gravel was found to be a water content of 3.9% (9). This was the mixing water content used for the pit-run gravel.

3.1.2 Outwash Sand

The second of the three aggregates is known as the Hanna outwash sand, named for a town near the Valparaiso Moraine in northwestern Indiana. For convenience, the actual aggregate used for the outwash sand was obtained from the Western Materials Company in West Lafayette, Indiana. However, the gradation used was identical to that of the Hanna outwash sand. The West Lafayette version was also similar to the Hanna outwash sand in angularity, mineralogy, and percentage of calcareous materials. The aggregate used was from the
same source as the pit-run gravel (see Section 3.1.1), but a different gradation. This outwash sand has been used in previous work at Purdue University (21,28).

The gradation used for the outwash sand is given in Table 3. The properties of outwash sand are listed in Table 4. The fluff point for outwash sand is a water content of 6.0% (28). This was the mixing water content used for outwash sand.

3.1.3 Crushed Stone

The third of the three aggregates is a crushed stone, known as a modified class 5-D base mixture. The stone was mechanically crushed from limestone bedrock, so all of the faces of the stone are fracture surfaces. Like the pit-run gravel and outwash sand, the crushed stone has been used at Purdue University before and the gradation, source, and properties determined then (9,27).

The crushed stone was obtained from Erie Stone, Inc., of Huntington, Indiana. This quarry is listed as aggregate source No. 58 by the Indiana State Highway Commission, and source 35-1 by the Geologic Survey.

The material is a fossiliferous recrystallized limestone. There are some thin shale and sandstone beds as inclusions. The crushed stone has been dry-sieved
Table 3. Outwash sand gradation.

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Percent Passing</th>
<th>Percent Retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&quot;</td>
<td>100.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>100.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>99.7</td>
<td>0.3</td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>99.5</td>
<td>0.2</td>
</tr>
<tr>
<td>#4</td>
<td>97.6</td>
<td>1.9</td>
</tr>
<tr>
<td>#8</td>
<td>94.3</td>
<td>3.3</td>
</tr>
<tr>
<td>#16</td>
<td>90.7</td>
<td>3.6</td>
</tr>
<tr>
<td>#30</td>
<td>78.4</td>
<td>12.3</td>
</tr>
<tr>
<td>#50</td>
<td>38.3</td>
<td>40.1</td>
</tr>
<tr>
<td>#100</td>
<td>9.5</td>
<td>28.8</td>
</tr>
<tr>
<td>#200</td>
<td>2.4</td>
<td>7.1</td>
</tr>
<tr>
<td>pan</td>
<td>0.0</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 4. Outwash sand properties.

- Bulk Specific Gravity (SSD) 2.607 (ASTM C 127)
- Apparent Specific Gravity 2.707 (ASTM C 127)
- Absorption 1.20% (ASTM C 127)
- Mineral Filler (< #200 sieve) non-plastic (ASTM D 424)
and stored in containers at room temperature in the Bituminous Laboratory, Crissom Hall, Purdue University. Controlled batches can then be made according to the specified gradation.

The gradation used for the crushed stone is given in Table 5. The properties of crushed stone are listed in Table 6. The fluff point for crushed stone is a water content of 5.0%. However, Castedo (9) discovered that when foamed asphalt mixes with crushed stone were compacted at 5.0% moisture content, excessive bleeding of water and noticeable instability of the mix occurred. For this reason a mixing water content of 4.0% was used for the crushed stone.

3.2 Additives

Three different types of additives were used in this research. They were Silane, Lime, and Indulin. Additives were included in this study because of the history of poor performance by foamed asphalt mixtures with respect to durability (2,9,20,22,28). Previously the durability problem was handled in the field by assuring that the foamed asphalt was drained and sealed (20). However, if an effective and economical additive could be found which would improve foamed asphalt mixtures' resistance to deterioration, then foamed asphalt
Table 5. Crushed stone gradation.

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Percent Passing</th>
<th>Percent Retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&quot;</td>
<td>100.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>96.7</td>
<td>3.3</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>79.0</td>
<td>17.7</td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>66.0</td>
<td>13.0</td>
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<td>#4</td>
<td>43.5</td>
<td>22.5</td>
</tr>
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<td>#8</td>
<td>34.0</td>
<td>9.5</td>
</tr>
<tr>
<td>#16</td>
<td>25.0</td>
<td>9.0</td>
</tr>
<tr>
<td>#30</td>
<td>17.1</td>
<td>7.9</td>
</tr>
<tr>
<td>#50</td>
<td>14.0</td>
<td>3.1</td>
</tr>
<tr>
<td>#100</td>
<td>11.5</td>
<td>2.5</td>
</tr>
<tr>
<td>#200</td>
<td>9.0</td>
<td>2.5</td>
</tr>
<tr>
<td>pan</td>
<td>0.0</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Table 6. Crushed stone properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Specific Gravity (SSD)</td>
<td>2.696</td>
<td>(ASTM C 127)</td>
</tr>
<tr>
<td>Apparent Specific Gravity</td>
<td>2.741</td>
<td>(ASTM C 127)</td>
</tr>
<tr>
<td>Absorption</td>
<td>1.28%</td>
<td>(ASTM C 127)</td>
</tr>
<tr>
<td>Mineral Filler (&lt; #200 sieve) non-plastic</td>
<td>1.28%</td>
<td>(ASTM D 424)</td>
</tr>
</tbody>
</table>
would be a much more viable alternative to other forms of bituminous materials.

3.2.1 Silane

The Silane used in this study is an amino functional organo Silane, and has been found to improve adhesion between bitumen and aggregate (15).

Silane coupling agents were originally marketed as an additive to improve the water resistance of reinforced plastics. Then it was noticed that initial properties of laminates were improved by introducing Silanes -- hydrophilic mineral surfaces were used in preparing laminates, and organic polymers with Silanes were used to improve the bond. Such a polymer-glass system was observed as being similar to an asphalt-mineral aggregate system, so it was decided to be worth investigating (14).

The Silane used in this investigation has the properties listed in Table 7.

Silane can be added to an asphalt mix in one of two ways -- either added to the asphalt itself, or added to the aggregate as a pretreatment. In this study, it was added to the aggregate.

Two concentrations of Silane were studied in the water sensitivity test, while only the higher
Table 7. Silane properties (after ref.15).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>clear liquid (CTM 0176)*</td>
</tr>
<tr>
<td>Color</td>
<td>light straw to yellow (CTM 0176)</td>
</tr>
<tr>
<td>Viscosity</td>
<td>6 cst (CTM 0004)</td>
</tr>
<tr>
<td>Specific Gravity (25°C)</td>
<td>1.02 (CTM 0001A)</td>
</tr>
<tr>
<td>Flash Point, Cleveland Open Cup</td>
<td>260°F (127°C) (CTM 0006)</td>
</tr>
</tbody>
</table>

*CTM stands for Corporate Test Methods, and they generally correspond to ASTM standard tests. CTMs are available from Dow Corning upon request.
concentration was used in the freeze-thaw test. The additive quantities used here were 0.08 and 0.17 pounds of Silane per 100 pounds of water. Three pounds of the Silane-water solutions are then used per 97 pounds of aggregate. These are such low concentrations of Silane that they were made into two stock solutions. When making the specimens, the solutions were added to the aggregate in the ratio of 3 to 97. Then the rest of the water needed to bring the specimens to the designated water content was added to the aggregate. The remainder of the specimen preparation (adding foamed asphalt, mixing, compacting, etc.) continued from there.

3.2.2 Lime

The lime used in this study was Ca(OH)$_2$, known as calcium hydroxide or hydrated lime.

Lime-treated soil is one of the oldest techniques for road construction. The Romans were known to have used it several hundred years B.C. (13). Lime is such an effective treatment that it is still used today.

Adding lime to a moist soil decreases the plasticity of cohesive soils and increases the workability. Once this occurs, the fine-grained soils begin to aggregate. This is a fairly quick reaction. Ultimately, the maximum density obtainable is lower than
untreated soil, and the optimum moisture content for compaction is increased. Adding only 1 or 2 percent lime to fine-grained soils has been found to reduce plasticity and improve mixing with asphalt (13).

The calcium hydroxide used in this investigation was of the lot analysis listed in Table 8.

The lime in this study was added in the form of a slurry which was thoroughly mixed with the aggregate before the foamed asphalt was introduced. The water used to make the slurry was the water needed to bring the aggregate to the desired water content.

Two different percentages of lime were studied in the water sensitivity test, while only the higher level was employed in the freeze-thaw test. The percentages utilized here were 1% and 2% by dry weight of aggregate. These levels have been found to be quite effective in the past and are generally the ones specified in practice.

3.2. Indulin

The anti-stripping agent used in this investigation was Indulin, which is a conventional anti-stripping agent. It is a heat-stable amine-based asphalt adhesion agent that can be incorporated with most hydrophobic and hydrophilic aggregates.
Table 8. Calcium hydroxide lot analysis.

\[
\text{Ca(OH)}_2 \quad \text{F.W.} = 74.09
\]

- Chloride (Cl) \quad 0.01\%
- Iron (Fe) \quad 0.05\%
- Sulfur Compounds (as \( \text{SO}_4 \)) \quad 0.06\%
- Heavy Metals (as \( \text{Pb} \)) \quad 0.002\%
- Magnesium and Alkali Salts \quad 0.62\%
- Insoluble in Dilute HCl \quad 0.006\%
Indulin is used to improve the adhesion of bituminous material to aggregate. It has been mixed with a variety of hot and cold bituminous-aggregate mixtures. Bonding characteristics have improved while the likelihood of the asphalt stripping from the aggregate has decreased when Indulin has been used (30).

The anti-stripping agent Indulin has the properties listed in Table 9.

The Indulin was added to the asphalt in the Foamix machine before the asphalt was foamed. To see if the additive had any effect on the ability of the asphalt to foam, the expansion ratio and half-life tests were made with the AC-20 asphalt-Indulin mixture. See Section 3.3.2 for data. The only immediately noticeable difference between AC-20 and AC-20 with Indulin was that the latter had an unusual odor to it, somewhat akin to cooked corn.

Two concentrations of Indulin were used in this investigation. Both concentrations were used in the water sensitivity test, while only the higher of the two concentrations was used in the freeze-thaw test. The concentrations worked with in this study were 0.30% and 0.60% by weight of the asphalt. Two cans of asphalt were used to make up stock solutions of AC-20 asphalt and Indulin -- one can for each concentration
Table 9. Indulin properties (after ref. 30).

<table>
<thead>
<tr>
<th>Active ingredients</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form</td>
<td>viscous liquid</td>
</tr>
<tr>
<td>Color</td>
<td>dark brown</td>
</tr>
<tr>
<td>Specific Gravity, 77° F/122° F</td>
<td>0.970/0.963</td>
</tr>
<tr>
<td>Pour Point</td>
<td>55° F</td>
</tr>
<tr>
<td>Viscosity, SSF</td>
<td>122° F</td>
</tr>
<tr>
<td>Viscosity, CPS</td>
<td>77° F</td>
</tr>
<tr>
<td>Viscosity, CPS</td>
<td>122° F</td>
</tr>
<tr>
<td>Flash point, Cleveland Open Cup</td>
<td>320° F</td>
</tr>
<tr>
<td>Fire point, Cleveland Open Cup</td>
<td>335° F</td>
</tr>
<tr>
<td>Weight/gallon</td>
<td>77° F</td>
</tr>
</tbody>
</table>
of anti-stripping agent. Whenever the Indulin-asphalt mixture was needed, the untreated asphalt was drained out of the Foamix™ machine, and the Indulin-asphalt mixture was heated in a 250°F oven and poured into the Foamix™ machine. The lines from the Foamix™ heater to the spray nozzle were always thoroughly saturated with the Indulin-asphalt mixture before the Indulin-asphalt was foamed onto any prepared aggregate. The procedure was repeated when untreated asphalt was again needed in the Foamix™ machine.

3.2.4 Control Specimens

A full series of specimens were made without any additives whatsoever. These were the control specimens. One set of control specimens was made for the water sensitivity test, and another set was made for the freeze-thaw test.

It was necessary to make a series of control specimens in order to judge the overall effect of the additives. Otherwise, it would only have been possible to see the relative effect between additives.

3.3 Bituminous Material

3.3.1 Asphalt Cement AC-20

Several asphalts from various sources were tested prior to this phase of the investigation (8). They
determined the foaming characteristics of these asphalts which are commonly used in Indiana. The foaming characteristics studied were expansion ratio and half life. The AC-20 with a penetration (0.1 mm) of 42 was chosen as having the best foaming characteristics.

This AC-20 was found to have the properties listed in Table 10. The foaming characteristics -- expansion ratio and half life -- were determined when the asphalt was at 325°F and 2% cold water was introduced to create the foam (10).

3.3.2 Asphalt Cement AC-20 with Indulin

The effect that an additive such as Indulin would have on the foaming characteristics of a bituminous material was unknown. When it was determined that the anti-stripping agent would be added to the asphalt before it was foamed, it was also decided that the foaming characteristics should be checked to see if there were any changes in them due to the additive.

All other variables in the test were kept constant -- the asphalt temperature was 325°F and 2% cold water was used for foaming. The test was conducted a sufficient number of times to provide a reasonable average. The expansion ratio was found to be 12, and the half life almost 13 seconds. It appears that the Indulin had a small effect on the foaming characteristics, but
Table 10. AC-20 properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration (0.1 mm), 100 g, 5 sec., 77° F</td>
<td>42</td>
</tr>
<tr>
<td>Softening point, Ring and Ball</td>
<td>118° F</td>
</tr>
<tr>
<td>Ductility of 77° F (25° C), 5 cm/min</td>
<td>150 cm</td>
</tr>
<tr>
<td>Kinematic Viscosity, 300° F (150° C)</td>
<td>229 cst</td>
</tr>
<tr>
<td>Kinematic Viscosity, 325° F (160° C)</td>
<td>126 cst</td>
</tr>
<tr>
<td>Kinematic Viscosity, 350° F (180° C)</td>
<td>72 cst</td>
</tr>
<tr>
<td>Expansion Ratio</td>
<td>13</td>
</tr>
<tr>
<td>Half Life</td>
<td>14 sec</td>
</tr>
</tbody>
</table>
the bituminous material was still suitable for use in foaming.

3.3.3 Percents of Asphalt Used

The percents of asphalt by dry weight of aggregate employed in this research were chosen based on previous research. Shofstall (28) and Castedo (9) performed several tests with the three aggregates used in this study in combination with a range of foamed asphalt contents. Judging by the different ways the mixtures behaved, an "optimum" foamed asphalt content was picked for each of the three aggregates. They are as follows: (a) 4.00% for pit-run gravel; (b) 4.25% for outwash sand; and (c) 4.50% for crushed stone.

Another foamed asphalt content for each of the aggregates was to be studied. This was so the effect of different levels of asphalt on durability could be determined. Shofstall (28) and Castedo (9) found that with foamed asphalt contents lower than the "optimum" ones listed above, there was an obvious lack of durability. For this reason, foamed asphalt contents 1% higher (by dry weight of aggregate) for each of the aggregates were specified: (a) 5.00% for pit-run gravel; (b) 5.25% for outwash sand; and (c) 5.50% for crushed stone.
Both foamed asphalt contents for each aggregate were used in the water sensitivity tests; only the lower level in each case was used in the freeze-thaw tests.

3.4 Specimen Preparation Equipment

Several pieces of equipment were used in preparing the 2 1/2" high by 4" diameter foamed asphalt specimens.

This equipment will be described in the paragraphs to follow.

3.4.1 Foamed Asphalt Generator and Mixer

The Laboratory Foamix™ Asphalt Dispenser, developed by the Continental Oil Company (CONOCO), was the primary piece of equipment for this experimental study. A picture of this device is shown in Figure 3.

The main components of the device are a two gallon heated asphalt storage tank, an outlet nozzle where the hot asphalt, cold water, and air come together, and a control panel where the various rates are adjusted.

The procedure for using the foamed asphalt dispenser follows.
FIGURE 3. LABORATORY FOAMIX™ ASPHALT DISPENSER
First, if there was enough asphalt in the storage tank, the main power, and quick heaters were turned on (all switches and knobs are on the control panel). The temperature gage was gradually set up to 325°F. Setting the gage to 325°F immediately could cause damage to the heating unit. The dispenser is heated by a tubular heater connected in series which heats the storage tank, asphalt pump, asphalt lines, and the foam nozzle. The heating process generally takes two to three hours. A dial gage monitors the temperature of the asphalt.

In the event that asphalt needed to be added to the tank, it was first heated in an oven to about 250°F. Then it was poured into the top of the Foamix™ asphalt storage tank.

The gear pump can be turned on when the temperature gage indicates at least 275°F. This starts the asphalt circulating through the lines at a rate of 0.5 gallons per minute. When the asphalt is at 325°F, it is ready for preparing specimens.

The water flow was held constant for this research at 44 cc/min, or 2% of asphalt flow.

Next the amount of asphalt to be dispensed can be set by determining the asphalt delivery time. A graph was provided by CONOCO for this purpose. It features
the asphalt weight in grams on the x-axis and the asphalt delivery time in seconds on the y-axis. To use the graph, calculate the amount of foamed asphalt necessary for the batch in question, go up from that weight on the x-axis to the plotted line, and then go left to the y-axis and read the delivery time. Then set the dial on the control panel for that delivery time. "Fine tuning" of this dial setting should be made by taring a container, turning the asphalt, air, water, and timer switches to on, pushing the "start" button when all the lights on the control panel are lit, and finally weighing the tare to see how much asphalt was actually dispensed. Adjustments are then made to the asphalt delivery time dial. This procedure continues until the desired amount of asphalt is dispensed.

The foamed asphalt should always be dispensed and discarded once before dispensing onto the prepared aggregate.

The foamed asphalt is dispensed through the outlet nozzle. It is at the nozzle where the cold water (which has been atomized by air) meets the hot asphalt, and the foamed asphalt is created and sprayed out.

The next major piece of equipment is the mixer. A picture of the mixer can be seen in Figure 3 to the
left of the Foamix™ apparatus.

The mixer used here was a type N-50 Hobart rotary mixer equipped with a steel paddle. It is a sturdy mixer, but as a precaution any material retained on a #4 sieve was kept separated from the rest of the aggregate and not placed in the mixer. Material retained on a #4 sieve has been known to jam or break blades. In this study, then, the material on the #4 sieve was moistened with a spray bottle, added to the aggregate after the smaller material had been mixed by the mixer with the foamed asphalt, and then stirred altogether by hand. The uniformity of the mix did not appear to suffer any adverse effects from this procedure.

3.4.2 California Kneading Compactor

The California kneading compactor, made by the August Manufacturing Company, provided the compaction for the foamed asphalt specimens. The machine is pictured in Figure 4.

The compactor compacts specimens within a mold through a series of tamps provided by a roving ram. The ram face is a sector of a 4 inch diameter circle. The first stage is the semi-compaction stage used to set the specimen for the heavier final compaction. With the gage pressure set at 14.5, the ram pressure is 250 psi. Thirty tamps (1 minute) at this pressure are
FIGURE 4. CALIFORNIA KNEADING COMPACTOR
used for semi-compaction. When the gage pressure is set at 31.75, the ram pressure is 500 psi. One hundred fifty tamps (5 minutes) at this pressure provides the final compaction.

The ram is not heated during compaction. Even so, sticking of mixture to the ram face has not been a problem.

3.4.3 Riehle Compression Machine

The Riehle compression machine was used to apply a levelling-off vertical load to foamed asphalt specimens after compaction in the California kneading compactor. The machine is pictured in Figure 5.

A static load of 12,570 pounds (1000 psi) was applied at a head speed of 0.25 in/min. It was applied using the double plunger method. The double plunger method consists of having a cylinder above and below the specimen, and flush up against the specimen. The machine is then started and pushes the cylinders together (with the specimen in between) at the designated rate until the 1000 psi has been applied. Then the machine is reversed and the cylinders removed from either end of the specimen.

This machine was also used for extrusion of the specimen after the specimens had finished curing in
FIGURE 5. RIEHLE COMPRESSION MACHINE
their molds. The specimen and mold were placed over one of the cylinders mentioned above, and then an extrusion collar, slightly wider than the specimen, was placed on top of the mold. The machine was then started up at a convenient rate and it pushed down on the collar until the specimen was extruded. Then the compression machine was stopped and the specimen removed.

3.4.4 Ovens and Scale

An oven set at $104^\circ$ F was used to cure the specimens for 24 hours. The oven used was a Blue M, manufactured by the Blue M Electric Company, Blue Island, Illinois.

Another oven, a Hotpack from the Electric Hotpack Co., Inc., Philadelphia, Pennsylvania, was used for heating asphalt to $250^\circ$ F before being poured into the Foamix™ machine. It was also used for finding the final dry weight of destroyed specimens.

The Mettler scale, type P-3, number 228985, made by E. H. Sargent and Company, was used for all weighing purposes. It measures a maximum of 3000 grams, and the smallest division is one gram.
3.5 Specimen Durability and Testing Equipment

Foamed asphalt has a history of poor durability (2,9,20,22,28). Standard durability testing procedures such as water sensitivity have been found to be so harsh on foamed asphalt test specimens that the specimens sometimes disintegrate before they can be measured for strength. For this reason, new durability tests were developed and were used in this experiment. The equipment needed for these tests will be described in this section.

Methods for monitoring the strength of a specimen being tested over time should ideally be completely non-destructive. Otherwise it would be impossible to sort out what was being measured; for instance, was it the effect of cyclic freeze-thaw on the specimen that caused a given change in strength or the effect of a monitoring test such as resilient modulus on the specimen — or some combination thereof? Two "new" ways of monitoring a specimen's characteristics over time when subjected to durability tests will be investigated in this study — pulse-velocity and percent change in weight. The resilient modulus test and a modified Marshall test will also be investigated here. The equipment necessary for these tests will be described in the following sections.
3.5.1 Vacuum Saturation Apparatus

Vacuum saturation has been used in the past to measure an asphalt mix's sensitivity to water infiltration. The method used in this experiment was recommended by Ruckel, Acott, and Bowering (26), and is similar to one used for asphalt emulsions (4).

A picture of the apparatus needed for the vacuum saturation is seen in Figure 6.

The equipment used for this procedure was as follows: (a) a pump capable of drawing at least 100 mm Hg of vacuum; (b) a dessicator or similar sturdy airtight container which can withstand at least 100 mm Hg of vacuum; (c) a manometer to show the amount of vacuum being drawn; and (d) enough water at room temperature to submerge the specimens in the dessicator to 1/2" over the top surface of the specimens.

3.5.2 Freeze-Thaw Apparatus

The freeze-thaw durability test involved cyclic vacuum saturation, freezing, and thawing. The equipment needed for these cycles was as follows: (a) the vacuum saturation equipment listed in Section 3.5.1 and pictured in Figure 6; (b) a freezer capable of bringing the temperature down to a level sufficiently below freezing (32°F) to guarantee that any water inside the
FIGURE 6. VACUUM SATURATION EQUIPMENT
freezer is indeed frozen; (c) an area where the specimens could sit undisturbed and slowly come to room temperature; and (d) plenty of sealable, airtight plastic bags which will keep the specimens' moisture content fairly constant between cycles of vacuum saturation.

3.5.3 Pulse-Velocity Apparatus

The pulse-velocity equipment used in this study was the type specified in ASTM D 2845. A picture of the apparatus is in Figure 7. It was made by the James Electric Co.

This equipment is generally used for testing rocks. In fact, the pulse-velocity apparatus used in this research was borrowed from the Rock Mechanics Laboratory, Grissom Hall, Purdue University.

The apparatus was as follows: (a) a pulse generator unit with a pulse repetition rate fixed at a point somewhere between 20 to 100 repetitions per second; (b) two transducers which convert electrical pulses to mechanical pulses and then back again. The transducers should have flat faces and be sturdy enough to withstand a bituminous laboratory environment; (c) a preamplifier to be used if the voltage output of the receiving transducer is relatively low or if the display timing units are relatively insensitive; (d) a display and timing unit with an electronic counter with provisions
FIGURE 7. PULSE-VELOCITY EQUIPMENT
for time interval measurements or a time-delay generator. A calibrated cylinder should be included with the equipment in order to adjust the calibration if needed; (e) a stand such as is seen in Figure 7. This is not standard pulse-velocity equipment, but was needed for testing foamed asphalt specimens since the specimens are of a larger diameter than the transducers. This stand allowed for the specimens to always be tested in the center; and (f) plenty of grease to assure a "perfect" seal between the transducers and the specimen ends.

3.5.4 **Diametral Resilient Modulus Device**

The resilient modulus machine employed in this research is shown in Figure 8. It is similar in principle to the one shown in the Basic Asphalt Emulsion Manual (4), although arranged somewhat differently.

The basic parts of the machine are a compressed air source, solenoid valve, piston, loading frame, measuring units, and a two channel chart recorder.

The solenoid valve produced the compressed air pulses, monitored by a pressure regulator, which in turn caused the piston to deliver a pulsating load to the top of the loading frame.
FIGURE 8. RESILIENT MODULUS EQUIPMENT
The specimen was placed underneath the loading frame resting on its side between two stainless steel strips. Thus the load was applied across a vertical diameter. The load was a constant 50 lb. impulse load which was applied every 3 seconds with a dwell time of 0.1 seconds. This level of loading was intended to provide a reasonable measurement of the characteristics of the specimen without causing damage to the specimen. The stainless steel strips were used only to hold the specimen in place just enough so that the rest of the specimen was free to deform from the loading. The strips were 1/2" wide and curved to fit a 4" diameter specimen.

The deformations were measured by two Linear Variable Differential Transformers (LVDTs). They were mounted vertically, on either side of the specimen and equidistant from it. Two LVDTs were used so that their results could be averaged in the event of uneven loading of the specimen. Each LVDT had its own pen on the chart recorder.

The equipment had to be calibrated every time it was used. A voltage was selected which regulated the degree of sensitivity of each pen on the chart recorder. Then the LVDTs were placed in a specially designed micrometer, one at a time, and the chart was calibrated. A steel cylinder of the same diameter as a
foamed asphalt specimen (4") was then placed in the apparatus. It received a series of pulsed loads so that the effects of machine deformation could be accounted for.

3.5.5 Marshall Testing Apparatus

The Marshall testing machine used in the experiment is shown in Figure 9. It was made by Rainhart Co.

The machine conforms to the specifications in ASTM D 1559. It is electrically powered and applies a load through semi-circular heads at the constant rate of 2 inches/minute. The load cell is connected to a chart recorder which automatically plots Marshall stability (in pounds) as a function of flow (in 10\(^{-2}\) inches). Three different stability plotting ranges are available depending on the estimated stability of the specimen. They are 0–2500 pounds, 0–5000 pounds, and 0–10,000 pounds. The intermediate range was generally appropriate in this investigation.
FIGURE 9. MARSHALL TESTING EQUIPMENT
CHAPTER 4

EXPERIMENTAL PROCEDURES

4.1 Specimen Preparation

The foamed asphalt mix specimens were prepared three at a time, and in the following manner:

1) The foamed asphalt generator was heated and prepared for use as described in Section 3.4.1.

2) The aggregate retained on a #4 sieve was weighed and placed in three pans, each pan having the same specified gradation.

3) A mixing bowl of the type used by the mixer described in Section 3.4.1 was used to hold enough of the aggregate passing a #4 sieve for three specimens. The aggregate passing a #4 sieve was weighed into the mixing bowl according to the specified gradation.

4) Water was added to the mixing bowl and aggregate passing a #4 sieve. The amount of water added depended on the mixing water content desired. The aggregate and water were stirred quickly and thoroughly
by hand. The mixing bowl and contents were then hooked up to the mixer, and stirred by machine for about 15 seconds.

5) A test expulsion of foamed asphalt was sprayed into a can and discarded (as explained in Section 3.4.1). Then the mixer was placed under the spray nozzle so that the foamed asphalt would spray directly onto the moistened aggregate. The mixer was turned on and the foamed asphalt dispensed. The mixer continued stirring the foamed asphalt mixture for two minutes after the foamed asphalt was added. The mixer was turned off. The mixing bowl was removed and the contents stirred by hand for another thirty seconds. Then a moistened towel was placed over the bowl to prevent moisture from escaping from the mixture, and the bowl was set aside briefly.

6) The three pans containing the aggregate retained on a #4 sieve were stirred and moistened with a spray bottle.

7) The foamed asphalt mixture was divided evenly into the three pans. Each pan was then well mixed to assure uniformity. The pans were covered by a moist towel to prevent moisture loss.

8) The California kneading compactor was prepared for use. A 4" inside diameter mold was put in
position, with three 1/4" shims underneath the mold and a 4" diameter piece of paper inside the mold to prevent sticking to the platen. Half of the foamed asphalt mixture from one of the three pans was spooned into the mold. The material in the mold was then rodded by a bullet-nosed 3/8" rod — 20 times in the center of the mold, and 20 times around the edge of the mold. The rest of the material in the pan was spooned into the mold and rodded in the same manner as the first layer.

9) The kneading compactor was set to 250 psi foot pressure for 30 tamps (1 minute), and the compaction started. At the end of this semi-compaction stage, the three 1/4" shims were removed from under the mold. The mold was pushed down flush with the platen, and the foot pressure set to 500 psi for 150 tamps (5 minutes). At the end of this compaction, the mold and specimen were removed from the kneading compactor.

10) The mold and specimen were placed in the Riehle compression machine in order to receive the 1000 psi static load by the double plunger method (see Section 3.4.3). Before putting the top plunger into the mold, a 4" diameter piece of paper was placed on top of the specimen to prevent sticking. The bottom piece of paper was still in place from compaction. When the specimen was ready, the static load was applied.
11) After the static load had been accomplished, the specimen was placed on a shelf and allowed to cure in the mold on its side at room temperature for 24 hours.

12) The other two pans of foamed asphalt mixture were prepared in a similar manner (steps 8-11).

13) Next, the specimens were extruded by the Riehle compression machine. The 4" diameter pieces of paper were removed from either end of the specimens, and the specimens were measured for height and weighed. Then, the specimens were placed in an 104°F oven to cure for 24 hours. The specimens were turned over halfway through this 24 hour oven cure.

14) At the end of the oven curing, the specimens were removed from the oven. The specimens were allowed to come to room temperature, then weighed. Thereupon they were ready for testing. A dummy specimen which had been heated in the oven with the other specimens was used to indicate when the specimens were at room temperature throughout. The dummy specimen was a foamed asphalt mix specimen which was never tested, but had a thermometer inserted to its middle and a cork at the surface of the specimen to insulate the thermometer.
All specimens were prepared in this way whether they were used as a control, for water sensitivity testing, or for freeze-thaw testing.

4.2 Durability Study

The main purpose of this report was to determine the durability characteristics of foamed asphalt mix specimens. The characteristics were investigated by conducting a water sensitivity test and a freeze-thaw test. Untested specimens were also investigated as a control.

The ability of foamed asphalt mix specimens to withstand durability testing in the past has generally been poor, as was mentioned previously. Consequently, three additives were incorporated in this study, as well as the untreated specimens. All specimens with additives and without additives had their durability characteristics determined as indicated in the paragraph above.

4.2.1 Water Sensitivity Procedure

The vacuum saturation apparatus described in Section 3.5.1 was used here.

Foamed asphalt mix specimens have been subjected to water sensitivity testing before, but the procedure
used was often too harsh (9,28). Briefly, the vacuum saturation procedure used previously was this: (a) specimens were cured, then measured for height and weight; (b) specimens were placed in an airtight container, and a vacuum of 30 mm Hg was drawn. This vacuum was held for one hour; (c) room-temperature distilled water was allowed to slowly enter the vacuum chamber until the specimens were submerged and had at least 1/2" of water above their top surfaces; (d) the vacuum was released and the specimens left soaking for 24 hours; and (e) specimens were removed from the water, weighed saturated-surface-dry, and tested.

There is little point to using a test if it is so harsh that after only one cycle there is no specimen left to monitor. Consequently, a less harsh test recommended by Ruckel, Acott, and Bowering (26) was used.

The procedure is quite similar to one found in the Asphalt Emulsion Manual by the Asphalt Institute (4):

1) After curing, weighing, and measuring, place selected specimens in a vacuum dessicator from which all dessicant has been removed, or similar suitable container.

2) Cover specimens with room-temperature water to 1/2" above their upper surface. Put lid in place and connect vacuum system.
3) Evacuate dessicator to 100 mm Hg absolute pressure and hold for 60 ± 5 minutes.

4) Slowly release vacuum and allow the specimens to soak in the water for 60 ± 5 minutes.

5) Remove specimens and weigh in saturated-surface-dry condition.

6) Test specimens by the selected procedures.

For a picture of some of the equipment used for vacuum saturation, see Figure 6.

4.2.2 Freeze-Thaw Procedure

The freeze-thaw testing procedure consisted of the following:

1) Test specimens for pulse-velocity (for pulse-velocity procedure, see Section 4.3.1).

2) Test specimens for resilient modulus (for resilient modulus procedure, see Section 4.3.2).

3) Conduct vacuum saturation as stated in Section 4.2.1 (steps 1-5).

4) Put specimens into plastic bags and seal the bags.
5) Place the bagged specimens in the freezer. Close the door and turn on the freezer. Leave the freezer on overnight.

6) Turn off the freezer the next morning and allow the specimens to thaw in the bags at least until the dummy specimen (described in Section 4.1) indicates that it is thawed in the center.

7) Weigh the specimens.

8) Repeat steps 1-7.

9) After the last freeze-thaw cycle to be conducted has been finished, test the specimens in the Marshall apparatus (for modified Marshall procedure, see Section 4.3.3).

10) Weigh remainder of specimens and place in 230° F oven to determine water content.

4.2.3 Control Testing

The control testing refers to those specimens which were measured for resilient modulus and modified Marshall stability (for control testing in water sensitivity section), or percent change in weight, pulse-velocity, resilient modulus, and modified Marshall stability (for control testing in freeze-thaw section), without having undergone any vacuum saturation, freez-
ing, or thawing. In other words, immediately after curing these specimens were subjected to the full battery of testing and thus were destroyed (by the modified Marshall stability test) before any vacuum saturation, freezing, or thawing could occur.

The values resulting from all of these tests were used as the "original" values in graphs and calculations, when comparing these control-tested specimens with the durability-tested specimens.

In both the water sensitivity section and the freeze-thaw section, six specimens were made of each type of specimen. Three of these six specimens were used as control specimens in both sections. The results of a given set of three specimens were averaged together to yield the "original" values.

4.3 Testing Routine

Several tests were used to quantify the effects of the durability tests and the additives on the foamed asphalt mix specimens in this study. In the water sensitivity section of testing, resilient modulus and modified Marshall stability were the quantifying tests. In the freeze-thaw section of testing, the percent change in weight, pulse-velocity, resilient modulus,
and modified Marshall stability were the quantifying tests.

The procedures for these tests will be described here.

4.3.1 **Pulse-Velocity Test**

The pulse-velocity test was used only in the freeze-thaw study. The foamed asphalt mix specimens were prepared, cured, weighed, and measured for height prior to pulse-velocity testing. The control-test specimens were measured for pulse-velocity once before being destroyed by Marshall testing. The freeze-thaw specimens were measured for pulse-velocity after each freeze-thaw cycle (with a few exceptions — see data in Appendix B).

The pulse-velocity procedure used in this study was as follows:

1) The machine was set up. The control unit was plugged into an outlet. The transducer wires were connected to the control unit — one to the "transmit" post, the other to the "receive" post. The transducer wires were connected to the transducers, and the transducers placed in the specimen stand.

2) The machine was checked for calibration. Grease was applied to the transducer faces and to the
ends of the calibration cylinder. The cylinder was placed in the specimen stand between the transducers. The transducers and the cylinder were pushed together and the transducers turned slightly so that a good seal was formed between the faces of the transducers and the cylinder ends. The machine was switched on and a pulse sent through the calibration cylinder. The reading on the display was adjusted (if necessary) until it agreed with the calibration value. The calibration cylinder was then removed and the grease cleaned off.

3) Grease was applied to the top and bottom of the foamed asphalt mix specimen to be tested. Grease was only necessary in the center of these faces because the transducers were of a smaller diameter than the specimens. The foamed asphalt mix specimen was placed on its side in the specimen stand. The transducers were placed in the transducer stands, which in turn rested in the specimen stand. The transducers and the specimen were pushed together and the transducers turned slightly so that a seal was formed between the faces of the transducers and the specimen ends. A pulse was sent through the specimen. While the pulse was being transmitted, the transducers were pushed against the specimen until the lowest value for that specimen was seen on the display (the value on the display being the number of microseconds — $10^{-6}$).
seconds — it took for a transmitted pulse to be received). Sufficient pressure was applied to the transducers to yield what was felt to be a representative value. The pressure was approximately the same for all specimens every time they were tested for pulse-velocity. The representative value on the display was recorded.

The specimen stand held the specimen still while it was being tested. The transducer stands enabled the specimen to be tested consistently through the specimen's center.

The recorded value was in microseconds. A pulse-velocity value was calculated from the recorded microsecond value by dividing the height of the specimen by the recorded microsecond value. The velocity units used in this study were centimeters per second (cm/sec).

4.3.2 Resilient Modulus Test

The resilient modulus test was used in both the water sensitivity and freeze-thaw studies. The foamed asphalt mix specimens were prepared, cured, weighed, and measured for height prior to resilient modulus testing. The control-test specimens were measured for resilient modulus once before being destroyed by Marshall testing. The water sensitivity specimens were
subjected to one cycle of vacuum saturation, and then
tested for resilient modulus and modified Marshall sta-
bility. The freeze-thaw specimens were tested (when
thawed) for resilient modulus every few cycles until
they, too, were destroyed by Marshall testing.

The resilient modulus procedure used in this study
was as follows:

1) Warm up the resilient modulus machine by plug-
ging it into the outlet, turning on the voltmeter, and
turning on the chart recorder. Allow the machine to
stand this way for at least 30 minutes before testing
begins.

2) Select a chart speed.

3) Calibrate the linear variable differential
transformers (LVDTs). The calibration of the LVDTs
consists of (a) placing the LVDTs one at a time into a
holding frame with a micrometer; (b) sliding a cylinder
through the LVDT so that it rests on the micrometer;
(c) selecting a voltage on the chart recorder (the vol-
tage controls the sensitivity of the recording pen — a
voltage is chosen such that the specimen’s resilient
modulus readings will be within the range of the
chart); and (d) moving the micrometer a known distance
to calibrate the chart.
4) Put the LVDTs back in the testing frame.

5) Place the 4'' diameter steel cylinder on the curved stainless steel strips and apply a pulsed load identical to the loading which will be applied to the foamed asphalt mix specimens. Any deformation indicated by the LVDTs (as shown on the chart recorder) will be subtracted out as machine softness.

6) Remove the steel cylinder and put the specimen to be tested in its place. Begin the 50 pound impulse load with a 3 second recurrence interval and a 0.1 second dwell time. Continue loading the specimen until it appears that the response of the specimen is roughly the same with each pulse. Stop the loading.

7) Rotate the specimen approximately 90°. Repeat the loading as in Step 6. If the readings in the two locations do not appear similar, repeat again in a third location.

The data are reduced by dividing the length of the downstroke (which is the amount of deformation the specimen recovers after the impulse load) by the calibration (the amount a chart pen moves when the LVDT connected to it is moved through a known distance. This dividend is called the instantaneous resilient vertical deformation ($V_{RI}$). To calculate the resilient modulus, the following is used:
\[ M_R = \frac{3.59 \, P}{h \, V_{RI}} \]

where \( M_R \) = instantaneous resilient modulus, psi

\( P \) = repeated load, pounds (in this study, 50 pounds)

\( h \) = height of specimen, inches

\( V_{RI} \) = instantaneous resilient vertical deformation, inches

4.3.3 Modified Marshall Stability

The modified Marshall stability test was used in both the water sensitivity and freeze-thaw studies. The foamed asphalt mix specimens were prepared, cured, weighed, and measured for height prior to modified Marshall stability testing. The term "modified" is used to indicate a test temperature at approximately 72° F. Resilient modulus testing had to be completed before the stability test. If the pulse-velocity test was to be conducted, it, too, had to be done beforehand.

In the freeze-thaw section of durability testing, all three of the nondestructive tests (pulse-velocity, resilient modulus, and percent change in weight) were conducted several times on each specimen over a period of weeks so the results could be compared per specimen. Since the Marshall test is destructive, it could only be done one time per specimen. In order to have
Marshall stability values at different intervals over the "life" of a specimen, several specimens of each composition were made. Three were destroyed by Marshall stability before any soaking, freezing or thawing, two were destroyed at what was felt to be a halfway point, and the last one was tested at disintegration. Thus, the resilient modulus, pulse-velocity, and percent change in weight values are charts of a single specimen's response. But the Marshall stability values are charts of six specimens' responses — the first point has three values averaged together, the second point has two values averaged together, and the final point has one value. It is felt that the Marshall stability values are representative of the actual stability values a single specimen would yield if it could have been tested several times throughout its "life" without being destroyed.

The modified Marshall stability procedure used in this study was as follows:

1) Warm up the Marshall testing apparatus by turning on the power switch and allowing the machine to stand for 15 minutes.

2) Select a range of stability for the chart. The choices are 0-2500 pounds, 0-5000 pounds, or
0-10,000 pounds. Indicate on the chart itself which range was selected.

3) Place the specimen between the semi-circular heads, and put the specimen and semi-circular heads underneath the load cell.

4) Set the chart so that it will automatically move at the load cell rate of 2 inches per minute. The chart plots stability (in pounds) versus flow (in $10^{-2}$ inches). One inch on the chart is equal to a flow of one. Thus the chart itself moves at a rate of 200 inches per minute.

5) Put a pen in the chart pen holder.

6) Begin loading the specimen. When the graph on the chart indicates that the load on the specimen is decreasing, cease loading.

The raw stability value is read from the chart recording depending on the chart range used. The raw stability value is then corrected for specimen height according to the Stability Correlation Ratio Table in The Asphalt Institute’s MS-2 manual. The flow is read directly from the chart recording, with one inch on the chart equaling a flow of one.
4.3.4 Percent Change in Weight

The percent change in weight was calculated only in the freeze-thaw study. The foamed asphalt mix specimens were prepared, cured, weighed, and measured for height. Then the cyclic freeze-thaw testing was begun.

The specimens were weighed after thawing and after vacuum saturation, just prior to freezing again. The percent change in weight was calculated by dividing the original weight into the difference between the current weight and the original weight. If the current weight was higher than the original weight, the percent change was indicated as positive. If the current weight was lower than the original weight, the percent change was indicated as negative. The original weight was defined as the weight of the specimen after preparation and curing, but before any vacuum saturation or freezing and thawing.

The specimens were weighed after every freeze-thaw cycle (with a few exceptions — see data in Appendix B).
CHAPTER 5
TEST RESULTS

5.1 Water Sensitivity

The water sensitivity testing was accomplished by using the vacuum saturation procedure recommended by Ruckel, Acott, and Bowering (26). The procedure is outlined in Section 4.2.1.

The effect of the water sensitivity testing was gauged by resilient modulus and modified Marshall stability. The procedures for resilient modulus and modified Marshall stability are outlined in Sections 4.3.2 and 4.3.3, respectively. The results of these two tests on the water sensitivity specimens and the corresponding control specimens are described in the following two sections.

5.1.1 Resilient Modulus

Resilient modulus values were lower for specimens that had undergone the water sensitivity test than for their corresponding control specimens, in 69% of the
cases. By aggregate, the percentages were thus: pit-run gravel — 8 of the 14 cases (57%); outwash sand — 11 of the 14 cases (79%); crushed stone — 10 of the 14 cases (71%). By additive, the percentages were thus: no additive — 4 of the 6 cases (67%); Silane — 6 of the 12 cases (50%); lime — 9 of the 12 cases (75%); Indulin — 10 of the 12 cases (83%). By foamed asphalt content, the percentages were thus: optimum percentage (for each aggregate) — 15 of the 21 cases (71%); optimum percentage + 1% (for each aggregate) — 14 of the 21 cases (67%).

Pit-run gravel foamed asphalt specimens on the average gained 10% in resilient modulus from the control (dry) specimens to the water sensitivity specimens. Outwash sand foamed asphalt specimens on the average gained 4% in resilient modulus from the control (dry) specimens to the water sensitivity specimens. Crushed stone foamed asphalt specimens on the average lost 14% in resilient modulus from the control (dry) specimens to the water sensitivity specimens. When all of the foamed asphalt specimens are considered together, the percent change in resilient modulus from the control specimens to the water sensitivity specimens comes out to 0%.

By additive, the percent change in resilient modulus from the control specimens to the water
sensitivity specimens resulted in these values: no additive — on the average, lost 17%; Silane — on the average, gained 32%; lime — on the average, lost 10%; Indulin — on the average, lost 13%.

By foamed asphalt content, the percent change in resilient modulus from the control specimens to the water sensitivity specimens resulted in these values: optimum foamed asphalt content (for each aggregate) — on the average, lost 12%; optimum +1% foamed asphalt content (for each aggregate) — on the average, gained 12%.

The highest resilient modulus value in this study — 520,000 psi — was obtained by a crushed stone control specimen with 0.005% Silane added and 4.50% foamed asphalt content. The Silane level was the higher of the two levels of Silane used in this study. The foamed asphalt content was judged to be optimum for this aggregate.

The lowest resilient modulus value in this study — 33,500 psi — was obtained by a crushed stone control specimen with 2.0% lime and 4.50% foamed asphalt content. The lime level was the higher of the two levels used in this study. The foamed asphalt content was judged to be optimum for this aggregate.
5.1.2 Modified Marshall Stability

Modified Marshall stability values were lower for specimens that had undergone the water sensitivity test than for their corresponding control specimens, in 88% of the cases. By aggregate, the results were: pit-run gravel -- 14 of the 14 cases (100%); outwash sand -- 12 of the 14 cases (86%); crushed stone -- 11 of the 14 cases (79%). By additive, the results were: no additive -- 6 of the 6 cases (100%); Silane -- 11 of the 12 cases (92%); lime -- 10 of the 12 cases (83%); Indulin -- 10 of the 12 cases (83%). By foamed asphalt content, the results were: optimum percentage (for each aggregate) -- 21 of the 21 cases (100%); optimum percentage + 1% (for each aggregate) -- 16 of the 21 cases (76%).

Pit-run gravel foamed asphalt specimens on the average lost 15% in modified Marshall stability from the control (dry) specimens to the water sensitivity specimens. Outwash sand foamed asphalt specimens on the average lost 19% in modified Marshall stability from the control (dry) specimens to the water sensitivity specimens. Crushed stone foamed asphalt specimens on the average lost 17% in modified Marshall stability from the control (dry) specimens to the water sensitivity specimens. When all of the foamed asphalt specimens are averaged together, the percent change in
modified Marshall stability from the control specimens to the water sensitivity specimens was a loss of 17%.

By additive, the percent change in modified Marshall stability from the control specimens to the water sensitivity specimens resulted in these average values: no additive — lost 46%; Silane — lost 15%; lime — lost 10%; Indulin — lost 13%.

By foamed asphalt content, the percent change in modified Marshall stability from the control specimens to the water sensitivity specimens yielded these results: optimum foamed asphalt content (for each aggregate) — on the average, lost 22%; optimum + 1% foamed asphalt content (for each aggregate) — on the average, lost 12%.

The highest modified Marshall stability value in this study — 9400 pounds — was obtained by a crushed stone control specimen with 1.0% lime added and 4.50% foamed asphalt content. This level of lime was the lower of the two levels of lime used in this study. The foamed asphalt content was judged to be optimum for this aggregate.

The lowest modified Marshall stability value in this study — 1130 pounds — was obtained by a pit-run gravel water sensitivity specimen without additives and with a 4.00% foamed asphalt content. The foamed
asphalt content was determined to be optimum for this aggregate.

5.2 Freeze-Thaw

The freeze-thaw testing was accomplished by coupling the vacuum saturation procedure used in the water sensitivity testing with a freezing and thawing routine. Vacuum saturation, freezing, and thawing were cycled and measurements made at intervals until the foamed asphalt specimens disintegrated. The whole procedure is outlined in Section 4.2.2.

The measurements made at intervals were pulse-velocity, resilient modulus, modified Marshall stability, and percent change in weight. The procedures for these tests are outlined in Sections 4.3.1, 4.3.2, 4.3.3, and 4.3.4, respectively. The results of these four tests on the freeze-thaw specimens and the corresponding control specimens are described in the following sections.

5.2.1 Pulse-Velocity

All of the specimens indicated a generally downward trend according to pulse-velocity; pulse-velocity values decreased with an increase in the number of freeze-thaw cycles. The pulse-velocity values did have a tendency to zigzag, however. A "best-fit" line would
yield a negative slope for each and every specimen (pulse-velocity decreases as freeze-thaw cycles increase), but individual pulse-velocity values show an occasional increase from a previous measurement.

The "best-fit" line for all of the specimens was either a straight line (as for some of the pit-run gravel and outwash sand specimens) or concave up (as for some of the pit-run gravel and outwash sand specimens, and all of the crushed stone specimens). If the "best-fit" line was concave up, then there was a faster rate of decrease for the early cycles, which tapered off to a slower, more constant rate of decrease for the later cycles. All three of the aggregates showed some zigzagging of values, with the pit-run gravel specimens being the most erratic.

Pulse-velocity values overall showed an average loss of 48% from the first measurement to the last measurement.

Pit-run gravel foamed asphalt specimens on the average lost 44% in pulse-velocity from first to last measurement. Outwash sand foamed asphalt specimens on the average lost 45% in pulse-velocity from first to last measurement. Crushed stone foamed asphalt specimens on the average lost 54% in pulse-velocity from first to last measurement.
When like additives are grouped together, the percent change in pulse-velocity from first to last measurement results in these values: no additive — average loss of 52%; Silane — average loss of 58%; lime — average loss of 28%; Indulin — average loss of 53%.

The highest pulse-velocity value in this study — 2.94 X 10^5 cm/sec — was obtained by a pit-run gravel specimen with 0.005% Silane and 4.00% foamed asphalt content. This velocity was measured before the specimen had undergone any vacuum saturation or freezing and thawing.

The lowest pulse-velocity value in this study — 0.80 X 10^5 cm/sec — was obtained by a crushed stone specimen with 0.005% Silane and 4.50% foamed asphalt content. This velocity was measured after the specimen's twenty-third cycle of vacuum saturation, freezing, and thawing, just one cycle before it was tested for Marshall stability.

5.2.2 Resilient Modulus

The resilient modulus results were as follows: some of the specimens showed a generally downward trend (that is, a decrease in resilient modulus values as the number of freeze-thaw cycles increased), some specimens had values which zigzagged to the extent that no trend
was apparent, and the rest were a mixture of the two preceding types.

The resilient modulus values occasionally show a downward trend in one graph or a section of graph when plotted versus an increasing number of freeze-thaw cycles, for pit-run gravel and outwash sand specimens. For the crushed stone specimens, a downward trend was always apparent. However, only the Indulin crushed stone specimens received a series of resilient modulus tests, and they were few in number.

Resilient modulus values showed an average loss of 36% from the first measurement to the last measurement when all of the specimens are taken into account.

Pit-run gravel foamed asphalt specimens lost 30% in resilient modulus overall from first to last measurement. Outwash sand foamed asphalt specimens lost 28% in resilient modulus overall from first to last measurement. Crushed stone foamed asphalt specimens lost 54% in resilient modulus overall from first to last measurement.

According to grouping by like additives, the percent change in resilient modulus from first to last measurement yielded these results: no additive — lost an average of 58%; Silane — lost an average of 17%;
lime — lost an average of 24%; Indulin — lost an average of 52%.

The highest resilient modulus value in this section of the study -- 803,300 psi -- was obtained by a crushed stone specimen with 0.6% Indulin and 4.50% foamed asphalt content. This resilient modulus was measured after the specimen had undergone four cycles of vacuum saturation, freezing and thawing.

The lowest resilient modulus in this section of the study -- 30,100 psi -- was obtained by an outwash sand specimen without additives, and with a 4.25% foamed asphalt content. This resilient modulus was measured after the specimen's twenty-first cycle of vacuum saturation, freezing, and thawing.

5.2.3 Modified Marshall Stability

All of the pit-run gravel and outwash sand specimens and most of the crushed stone specimens showed a decrease in modified Marshall stability as the number of freeze-thaw cycles increased. The Silane crushed stone specimens showed an increase in stability between the "halfway" point and the end point. The lime crushed stone specimens showed an increase in stability between the uncycled specimens and the "halfway" point (see Section 4.3.3 for explanation on Marshall freeze-thaw testing sequence).
Modified Marshall stability values showed an average loss of 70% from the first measurement to the last measurement when the specimens were all considered together.

Pit-run gravel foamed asphalt specimens lost an average of 74% in modified Marshall stability from first to last measurement. Outwash sand foamed asphalt specimens lost an average of 80% in modified Marshall stability from first to last measurement. Crushed stone foamed asphalt specimens lost an average of 51% in modified Marshall stability from first to last measurement.

When grouped by additives, the percent change in modified Marshall stability from first to last measurement was: 89% on the average for specimens without additives; 81% on the average for Silane specimens; 36% on the average for lime specimens; and 80% on the average for Indulin specimens.

The highest modified Marshall stability value in this section of the study — 7200 pounds — was obtained by a crushed stone specimen with 0.6% Indulin and 4.50% foamed asphalt content. The stability was measured on a specimen that did not undergo any vacuum saturation or freezing and thawing.
The lowest modified Marshall stability value in this section of the study — 75 pounds — was obtained by an outwash sand specimen with 0.005% Silane and 4.25% foamed asphalt content. This specimen had undergone vacuum saturation, freezing and thawing until it disintegrated.

5.2.4 Percent Change in Weight

All specimens gained weight after the initial vacuum saturation period. After that, for several of the early cycles, the specimens either slowly gained more weight, maintained their weight, or began slowly losing weight. There was always some slight zigzagging apparent when the percent change in weight of a specimen was plotted versus cycles of freezing and thawing. The pit-run gravel and outwash sand specimens which were tested until disintegration often showed an ever-increasing rate of weight loss. The crushed stone specimens generally lost weight at a more constant rate.

The percent change in weight values showed an average loss of 7% overall.

Pit-run gravel foamed asphalt specimens lost an average of 12% in weight from first measurement to last measurement. Outwash sand foamed asphalt specimens lost an average of 10% in weight from first measurement
to last measurement. Crushed stone foamed asphalt specimens lost an average of 0% in weight from first measurement to last measurement.

By additive, the percent change in weight results from first to last measurement were thus: no additive -- lost an average of 1% in weight; Silane -- lost an average of 12% in weight; lime -- lost an average of 1% in weight; Indulin -- lost an average of 14% in weight.

The highest percent change in weight -- an increase of 8% -- was obtained by an outwash sand specimen with 2.0% lime and 4.25% foamed asphalt content. This percent change in weight was reached after the specimen had undergone 18 cycles of vacuum saturation, freezing and thawing.

The lowest percent change in weight -- a loss of 29% -- was obtained by a pit-run gravel specimen with 0.6% Indulin and 4.00% foamed asphalt content. This percent change in weight was reached after the specimen had undergone 29 cycles of vacuum saturation, freezing and thawing, just before being destroyed by modified Marshall stability testing.
CHAPTER 6

DISCUSSION OF RESULTS

6.1 Water Sensitivity

Trends in the data were apparent in the water sensitivity section when considering the modified Marshall stability results for the pit-run gravel and outwash sand foamed asphalt specimens. It was more difficult to determine trends for the crushed stone foamed asphalt specimens. Crushed stone aggregate is an inherently strong material, so the effect of additives on crushed stone foamed asphalt specimens would be minimal.

Specimens without any additives generally had among the highest stabilities before being subjected to water sensitivity tests. After the test, however, specimens without additives had among the lowest stabilities.

Specimens with additives retained significantly higher percentages of modified Marshall stabilities after undergoing the water sensitivity test. The
Silane and Indulin additives appeared to have had a weakening effect on the control specimens — the control specimens being those not subjected to the water sensitivity test. After the water sensitivity test, however, the Silane and Indulin additives caused those specimens to retain sufficient modified Marshall stabilities that they had higher stabilities than the specimens without additives. Specimens with lime added benefitted both before and after the water sensitivity tests. Specimens with lime were as strong or stronger than specimens without additives before the water sensitivity test. After the test, lime-added specimens had a high retention of their initially high stabilities. Thus, specimens with lime consistently had the highest stabilities after the water sensitivity test.

A graph of the stability values for pit-run gravel specimens with 4.00% foamed asphalt content both before and after the water sensitivity test is shown in Figure 10. This graph is representative of the trends observed with the rest of the specimens.

Lime has performed favorably as an additive to asphalt cement mixes in the past (13). Lime performed well as an additive in the water sensitivity section most likely for the following two reasons: (a) lime is a hydrophilic material and so would tend to attract the water to itself. Thus, the water would be unable to
FIGURE 10. WATER SENSITIVITY AND CONTROL MODIFIED MARSHALL STABILITY VALUES FOR PIT-RUN GRAVEL SPECIMENS WITH 4.00% FOAMED ASPHALT CONTENT
cause stripping of the asphalt from the aggregate. Instead the water would be "fixed" by the lime; and (b) when used in small quantities such as was done in this study, lime, being a fine-grained material, serves to stiffen the asphalt matrix so that stability increases without the specimen becoming brittle.

Silane and Indulin both increase a foamed asphalt mix specimen's resistance to water by improving the bond between the asphalt and the aggregate. Both are liquid additives and so do not contribute any fine-grained material to the mix as does lime. Thus, the benefit of using Silane or Indulin, as opposed to no additive, is that they make it more difficult for water to get in between the asphalt and aggregate; the asphalt is less likely to strip off the aggregate because of water infiltration when Silane or Indulin is used. Neither Silane nor Indulin provide for any stiffening of the asphalt matrix; also, they do not draw the water to themselves and away from the asphalt-aggregate interface. Lime, however, does both of these things. These differences may help explain the various responses exhibited by the different type specimens.

There were two levels for each of the additives in the water sensitivity section. The modified Marshall stabilities for one type of additive were generally fairly close in value at the two levels for that type
of additive. For the Silane specimens, the higher level (0.005% vs 0.002%) usually had a slightly higher stability than the lower level. For the lime specimens, the higher level (2.0% vs. 1.0%) usually had a slightly higher stability than the lower level. For the Indulín specimens, the lower level (0.3% vs. 0.6%) usually had a slightly higher stability than the higher level. A more complete battery of tests would have to be conducted to determine the optimum level of each additive to use with each aggregate.

The crushed stone foamed asphalt mix specimens almost without exception had higher modified Marshall stabilities than the pit-run gravel or outwash sand specimens. The modified Marshall stabilities for pit-run gravel and outwash sand specimens were fairly close in range. The pit-run gravel stabilities were somewhat higher than the outwash sand stabilities, though. Crushed stone is a strong material and so was expected to yield the highest stabilities. Pit-run gravel and outwash sand were from the same source and so could be expected to yield similar stabilities. Since the pit-run gravel gradation had a slightly larger maximum aggregate size and higher percentages of the larger aggregates than the outwash sand, the pit-run gravel would most likely have slightly higher stabilities than the outwash sand. These logical expectations were
indeed observed in the laboratory.

With each aggregate two levels of foamed asphalt content were used — an "optimum" level and an "optimum + 1%" level based upon mix design procedures for the case of no additives. There did not seem to be much difference in modified Marshall stability between the two foamed asphalt contents within the water sensitivity section or the control section. The better foamed asphalt content would then be the lower level for each aggregate simply from an economics point of view.

The resilient modulus results did not indicate any discernable trends in the water sensitivity section. The various problems associated with the diametral resilient modulus machine will be discussed in more detail in Section 6.3.

6.2 Freeze-Thaw

Modified Marshall stability and pulse-velocity values both showed some trends in the freeze-thaw section of the durability testing. In fact, the trends seen in the stability and velocity values were comparable.

Crushed stone specimens again were inherently strong, so the effect of additives was minimal. Trends
and effects were much more visible with the pit-run gravel and outwash sand specimens.

Specimens without any additives usually had the lowest stability and pulse-velocity values, and disintegrated the fastest. It appears that any initial advantage that no-additive specimens have over specimens with additives (see reference to higher stability values for specimens without additives before they are subjected to the water sensitivity test, in Section 6.1) is quickly overshadowed by the benefits of additives with respect to durability.

Specimens with additives retained more of their original stability and pulse-velocity while being put through cycles of vacuum saturation, freezing and thawing than specimens without additives. Specimens with additives also had increased longevity. Lime was by far the best of the three additives. For pit-run gravel and outwash sand, the lime specimens had markedly improved modified Marshall stability over the no-additive specimens and Indulin and Silane specimens as well. Graphs of the modified Marshall stabilities versus number of freeze-thaw cycles for all three aggregates are presented in Figures 11, 12, and 13 (pit-run gravel, outwash sand, and crushed stone, respectively). The pulse-velocity values for the lime specimens were also consistently high (see Appendix B
FIGURE 11. MODIFIED MARSHALL STABILITY VALUES VERSUS NUMBER OF FREEZE-THAW CYCLES FOR PIT-RUN GRAVEL SPECIMENS
FIGURE 12. MODIFIED MARSHALL STABILITY VALUES VERSUS NUMBER OF FREEZE-THAW CYCLES FOR OUTWASH SAND SPECIMENS
FIGURE 13. MODIFIED MARSHALL STABILITY VALUES VERSUS NUMBER OF FREEZE–THAW CYCLES FOR CRUSHED STONE SPECIMENS
for specific values). Pit-run gravel and outwash sand specimens with lime had by far the highest number of freeze-thaw cycles to disintegration. In fact, the pit-run gravel and outwash sand specimens with lime were destroyed by the Marshall test prematurely in the interest of time. They could have easily existed far beyond the 60 cycles indicated in Figure 14.

The success of lime as an additive to foamed asphalt mix specimens can be attributed to the characteristics of lime mentioned in Section 6.1 (hydrophilic nature, stiffening effect). These beneficial characteristics of lime can be further substantiated in the freeze-thaw section of durability testing by observing two items: (a) lime is hydrophilic and causes the foamed asphalt specimens to which it is added to continue gaining water weight long after other specimens have begun losing weight; and (b) lime helps to retain stability of the specimens by stiffening and thus maintaining the integrity of the asphalt matrix.

6.3 Test Correlations

The pulse-velocity results and modified Marshall stability values present correlation possibilities between the two test methods. For practically all of the specimens in the freeze-thaw section, the pulse-velocity values closely paralleled the trends observed
FIGURE 14. LONGEVITY GRAPH--NUMBER OF FREEZE-THAW CYCLES SPECIMEN SURVIVES BEFORE DISINTEGRATING
with the modified Marshall stability values. Not only were similar rates of change apparent when comparing the two measurements, but relative values seemed to agree as well -- a high modified Marshall stability value often corresponded with high pulse-velocity values. An example of pulse-velocity and modified Marshall stability values for a specimen can be seen in Figure 15. The specimen shown is composed of outwash sand aggregate with 0.005% Silane and 4.25% foamed asphalt content.

Pulse-velocity values appear to have good reproducibility. Like specimens had similar pulse-velocity values when compared at a given number of freeze-thaw cycles. An example of pulse-velocity reproducibility for a given type of specimen can be seen in Figure 16. The type of specimen in this figure is a pit-run gravel without additives and with a foamed asphalt content of 4.00%.

Pulse-velocity values decreased with an increasing number of freeze-thaw cycles. This behavior would indicate that it takes the pulse longer to find a continuous path through the specimen as the number of freeze-thaw cycles accumulate, which seemed to be what was happening. From the appearance of the specimens, the discontinuity was happening faster on the perimeter of the specimens, but was also occurring on the inside
Figure 15. Pulse-Velocity - Modified Marshall Stability Comparison
FIGURE 16. PULSE-VELOCITY REPRODUCIBILITY
of the specimens. As time went on there were fewer and fewer continuous paths through the specimen. Both the pulse-velocity and modified Marshall stability values would be expected to decrease in this case, as indeed they did.

There were only two problems with the pulse-velocity test, and they might be easily solved. The first problem concerns the standard machine grease which was applied to both ends of each specimen so the transducers would have a better seal on both ends (routine pulse-velocity testing procedure). There was some slight indication that the grease may have been causing some local deterioration of the asphalt. It is not thought to have had a profound effect on the experiment. It may have caused a somewhat faster demise of the specimens. A more inert grease such as silicone grease (inert meaning non-reactive with the asphalt matrix) might have had less of a negative effect on the specimens. However, since the slightly detrimental effect of the standard machine grease was not noticed until the experiment was well under way, it was decided that consistency was the better route. Thus the standard machine grease was used throughout the experiment.

The other problem with the pulse-velocity test concerned the slight zigzagging of pulse-velocity values with time. While all specimens exhibited a
downward trend in pulse-velocity with time, there were occasional increases in pulse-velocity from time to time. If the zigzagging could be eliminated, the decrease in pulse-velocity with each freeze-thaw cycle would be more obvious (and easier to correlate). This is, of course, assuming that the zigzagging of values is caused by something other than the properties of the specimens themselves.

The slight zigzagging of pulse-velocity values may have been caused by a difference in pressure on the transducers from one pulse-velocity measurement to the next. A fairly constant pressure (applied by hand) was attempted from day to day, but there was no means of verifying how much pressure was actually applied. The amount of pressure applied to the transducers has not really been a factor with the pulse-velocity test prior to this experiment because pulse-velocity was previously used for testing stiffer materials such as rock. Asphalt specimens have much more "give" to them, and so a range of readings can be had depending on the amount of pressure applied to the transducers. A solution to this pressure problem might be to insert a device to measure the force applied between the specimen and the transducer. A standard force would need to be adopted.

Another cause for zigzagging might be tied to the disintegration of the specimen. As the specimen breaks
down under a series of freeze-thaw cycles, the surface is affected more than the inside of the specimen. Thus the surface material would be less continuous than the inside material. This phenomenon was observed during the experiment in the following way. When a significant amount of the surface material would slough off, then a more continuous, "unweathered"-looking surface would be exposed. A more continuous specimen, of course, yields a higher velocity. The higher velocity would only be temporary, however, since the newly exposed surface would quickly become as discontinuous as its predecessor. The downward trend would continue as the newly exposed surface become more "weathered." It is logical to expect the pulse-velocity values to decrease.

Assuming that the specimen "weathers" to roughly the same depth before that material sloughs off, then the ratio of "weathered," discontinuous material to more continuous material is constantly increasing. Also, there would be a shorter route for the water to travel to the center of the specimen each time some material sloughs off. This would enable the center of the specimen to deteriorate further.

A third cause might be related to the grease used between the transducers and the specimen. The purpose of this grease is to form a seal so that the pulse is transmitted directly from the transducer to the
specimen to the other transducer without having to cross an air gap at the transducer/specimen interfaces. When material began to slough off the specimens, the transducers had to be placed on an uneven surface. A large amount of grease was sometimes necessary to fill in the gaps where aggregate and asphalt had once been. Since the pulse-velocity test had been used for testing materials with smooth, even surfaces (such as rock) prior to this experiment, the use of large amounts of grease may have made a difference.

It should be noted that the pit-run gravel specimens yielded the most erratic results. This could probably be traced to the gradation for the pit-run gravel. There was a considerable range in size, shape, type, and density of aggregate. The pulse from the transducers would be sent through a great variety of material. The pit-run gravel specimens were much less uniform than the outwash sand (which had a smaller range of aggregate size) or the crushed stone (which was all one type of aggregate) specimens. The path of the pulse could be so different each time that it would result in somewhat erratic results. Also, because there was such a wide range in aggregate size, the pit-run gravel specimens presented the most uneven surfaces for the transducers as the asphalt and aggregate sloughed off (see explanation in paragraph above).
Resilient modulus results in both the water sensitivity section and freeze-thaw section were discouraging in terms of revealing trends or indicating possibilities for correlation with the modified Marshall stability test.

Several explanations are possible for the discouraging resilient modulus results: (a) the specimens have directional characteristics; (b) the specimens have "strong" days and "weak" days; (c) the testing apparatus needs refinement; (d) the test measures nothing and thus is invalid; (e) the specimens were not wholly thawed on some days and so appeared stronger; or (f) the resilient modulus is just an extremely sensitive parameter.

The likelihood of each explanation is examined in the paragraphs to follow.

(a) The specimens were rodded and compacted in such a way as to minimize or eliminate directional properties. Since each of the three gradations (pit-run gravel, outwash sand, crushed stone) contained a wide range of aggregate size that was randomly oriented within each specimen, directional properties are to be expected to some small degree. However, the difference in modulus from one test to the next for some specimens seemed far too great (practically doubling sometimes)
to be attributed to directional characteristics alone. Therefore, this explanation does not seem very likely.

(b) It has been shown extensively that laboratory specimens gain strength with age. It also stands to reason that a specimen subjected to cycles of freezing and thawing will lose strength. While it is conceivable that a specimen may gain more strength due to age than it loses due to a cycle of freezing and thawing, and perhaps appear "stronger" than the day before, it is not probable that the increase in modulus would be as great as was seen in these results. Therefore, this explanation may account for some small part of the erratic results, but is probably not a major factor.

(c) Some difficulty was encountered when using the resilient modulus testing equipment. First of all, owing to the nature of the specimens, the equipment came in contact with quite a bit of deleterious material -- fine aggregate, bits of asphalt, and moisture -- that came from the specimens. There are vertical guide bars on the machine which pass through holes on a crossbar with very small clearance. Any foreign matter could easily impede the progress of the crossbar (which moves with every pulse of the machine). Even a small impediment would drastically change the reading on this sensitive machine. Also, the machine was quite sensitive to other electrical machinery in the area,
sometimes making testing impossible. Even vibrations from a sizeable distance from the machine could affect the readings. There was some indication that humidity may have made a difference. The aforementioned vertical guide bars seemed to be much more prone to sticking in the holes during the humid summer than during the dry winter. Another problem involved the linear variable differential transformer (LVDT) on the right side. Although it was capable of being calibrated, it did not seem to function well during testing. On a rare occasion the results of the right and left LVDTs seemed to roughly agree, but generally the right LVDT showed a very small movement in the specimen or nothing at all. While it could be just an indication of a high modulus or slight misalignment of the specimen, it gave such results consistently — regardless of specimen or number of cycles a specimen had undergone. A fourth problem was the one of making sure the specimen to be tested was lined up squarely in the machine. Each specimen was tested such that it rested along its rounded sides. It was held in place by two bars — one underneath the specimen and one directly above — that were grooved to fit the specimen exactly. However, the bars were narrow enough to make it difficult to determine if the specimen was in the grooves squarely, or turned slightly. Since the measurements being made were so small (on the order of $10^{-4}$ inches), having the
specimen not quite square in the machine would cause a significant error in modulus measurement. Even a slight turn of the specimen — not detectable by eye — could result in a measurable difference. Furthermore, the specimens which had been soaked in water became rather pliable on their outer surfaces. This fact made getting the specimen squarely into the machine even more subject to error. The specimen could deform under its own weight so that it appeared to be well-seated in the grooves, when in fact it was not. This, too, would yield an erroneous modulus. The sum total of the problems mentioned in this paragraph could be the major reason for the erratic results.

(d) It stands to reason that the test indicates something. Specimens of differing compositions should logically respond in a measurably different way to a succession of fifty pound impulse loads. If the machine is consistent with itself and if the specimens are relatively uniform, then it seems reasonable to expect trends in the modulus values. It also seems likely that resilient modulus values for a single specimen should decrease with time if that specimen is undergoing a series of harsh durability tests, such as the freeze-thaw tests. Unfortunately, these trends were not apparent in enough of the tests to form specific conclusions. There was some indication in
several of the resilient modulus tests, however, that with some equipment modification the test might yield better results. Thus saying the resilient modulus test measures nothing cannot be an explanation, for there are differences to be measured and the resilient modulus test ought to have the capacity to detect the differences.

(e) Whenever the specimens were frozen and thawed, a dummy specimen (i.e., never tested or saturated) with a thermometer was always frozen and thawed along with them (see Section 4.1 for description of dummy specimen). The thermometer was implanted in the dummy specimen so that it measured the temperature in its center. It was assumed that when the center of the specimen was of a high enough temperature to be thawed, the whole specimen was thawed. Therefore, the chance is minute that the specimens sometimes gave falsely high moduli because of frozen areas within the specimens.

(f) It is true that the resilient modulus machine is making very sensitive measurements. However, it is not felt that the machine is actually measuring a legitimately sensitive parameter; the machine is sensitive, but the modulus is not.
Overall, then, it appears that the most likely reason the resilient modulus results were so erratic is because the testing apparatus needs refinement. To improve the results, the best thing to do with this apparatus would be to alleviate the sticking problem encountered by the vertical guide bars on the horizontal crossbar, and to make it easier to line the specimen up squarely in the machine. Widening the holes through which the vertical guide bars pass by a fraction might eliminate the sticking problem (which was significant enough to prevent the specimen from receiving the fifty pound impulse load altogether). Making the narrow grooved bars that hold the specimen in place slightly wider -- so that they would come in contact with more of the surface area on the sides of the specimen -- would better assure that the specimen was being tested squarely.

Percent change in weight showed increases in specimen weight in the early cycles of freeze-thaw testing for all of the specimens. This was most likely due to absorption of water during vacuum saturation and the addition of grease to the specimen ends for the pulse-velocity tests. Eventually the specimens began losing weight.

The percent change in weight does not give an indication of imminent failure. In viewing the percent
change in weight vs. number of freeze-thaw cycles graphs for all of the specimens tested until disintegration, there was no clue as to when the specimen was about to fail. While all specimens were in the process of losing weight, there was no significant change in pattern.

However, the percent change in weight would prove helpful when determining what asphalt percent, aggregate gradation, and type and amount of additive has the most beneficial effect on material retention. The specimen which retains the most material the longest would probably be the most durable in the field.
CHAPTER 7

CONCLUSIONS

This study investigated the durability of foamed asphalt specimens when subjected to a modified form of vacuum saturation for a water sensitivity test and cycles of freezing and thawing. The investigation was conducted using three kinds of aggregates, three types of additives (at two levels in water sensitivity, and one level in freeze-thaw), one type of asphalt (at two levels in water sensitivity, and one level in freeze-thaw), one mixing temperature, one testing temperature, and one set of curing conditions.

Four tests were used to monitor the durability of the foamed asphalt specimens. Three were "non-destructive" — resilient modulus, pulse-velocity, and weight measurements — and one was destructive — modified Marshall stability.

The following conclusions were made from an examination of the results described in this report, given
the scope of the project stated in the opening paragraphs of this section:

1. Vacuum saturation weakened the foamed asphalt specimens.

2. For outwash sand and pit-run gravel, the additives enabled the foamed asphalt specimens to retain much more of their original stability after vacuum saturation than untreated specimens. Additives had little effect on crushed stone specimens in the water sensitivity test. The crushed stone is limestone and so the specimens were inherently resistant to water.

3. Durability was generally better with higher levels of asphalt in water sensitivity testing. Lime and Silane additives resulted in better durability than would have been possible by the addition of more asphalt alone — the higher the level of additive, the better the resistance. Indulin improved durability better at lower levels of additive, but overall the effect was not large.

4. Cyclic vacuum saturation, freezing and thawing weakened the foamed asphalt specimens.

5. The additives enabled the foamed asphalt specimens to retain more of their original stability after
repeated freezing and thawing than the untreated specimens.

6. The additives caused the foamed asphalt specimens to last longer under cyclic freezing and thawing than the untreated specimens.

7. Lime was consistently the additive that produced the best performing mix. The improvement in the Marshall stability numbers, stability retention, and specimen longevity is such that a material generally less suitable for bituminous mix such as outwash sand or pit-run gravel gains so much from the addition of lime as to rival a material more suitable for bituminous mix such as crushed stone. The lime-treated outwash sand and pit-run gravel specimens had somewhat lower stability than the lime-treated crushed stone specimens, but they were able to withstand many more cycles of freezing and thawing before disintegrating.

8. Silane and Indulin appeared to yield favorable results for the foamed asphalt specimens in terms of stability retention and longevity; however, the results were not nearly so dramatic as for the lime-treated specimens.

9. Pulse-velocity is a non-destructive test that appears to be related to the modified Marshall
stability values obtained in this study. There are remarkably similar rates of decline per cycle for pulse-velocity and modified Marshall stability values. There also seems to be good reproducibility of pulse-velocity values among like specimens.

10. The resilient modulus results were too erratic to form a specific conclusion in the water sensitivity section. Resilient modulus showed some signs of promise in the freeze-thaw section, but there was still considerable scatter in the values. Changes in the resilient modulus testing apparatus appear necessary to reduce the scatter.

11. The percent change in the weight of a specimen as it undergoes cyclic vacuum saturation, freezing, and thawing does not correlate with a change in stability, and does not indicate when a specimen is near failure (failure being when a specimen splits).
CHAPTER 8
RECOMMENDATIONS FOR FUTURE RESEARCH

The following recommendations for future research were made on the basis of the findings in this investigation.

1. Improve the pulse-velocity test in two ways: (a) use a silicone grease between the specimen ends and the transducers to provide a seal without deteriorating the asphalt; and (b) determine a standard pressure, a method of pressure application, and a way of measuring the actual pressure induced, to be used with the pulse-velocity transducers against the specimen ends when taking pulse-velocity measurements.

2. Improve the resilient modulus test in three ways: (a) keep the machine as clean and free from electrical and vibrational interference as possible since it is making very sensitive measurements; (b) alleviate the problem of the crossbar
BIBLIOGRAPHY
becoming stuck on the vertical guide bars by making the holes in the guide bars slightly wider; and (c) widen the two narrow stainless steel strips which hold the specimen in place so that it is certain each specimen is being tested squarely.

3. Determine the optimum level for each additive, or a procedure for finding such a level.

4. Conduct a field study using a foamed asphalt mix with lime as an additive in a test pavement. It is important to see if lime is as beneficial in the field as it is in the laboratory.

5. Compare the durability of foamed asphalt mixtures with the durability of other mixtures having the identical gradation but different binders (i.e., asphalt cement, emulsions, and cutbacks).
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APPENDICES

The following Appendices to this Report are not included in this copy:

Appendix A  Water Sensitivity Test Results  pg 181 - 199
Appendix B  Freeze-Thaw Test Results  pg 200 - 266

A copy of each Appendix may be obtained for the cost of duplication by request to:

Joint Highway Research Project
Purdue University
Civil Engineering Building
West Lafayette, Indiana  47907