DYNAMIC MODULUS OF BITUMINOUS MIXTURES AS RELATED TO ASPHALT TYPE

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BY

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PURDUE UNIVERSITY AND
INDIANA STATE HIGHWAY COMMISSION

Final Report

DYNAMIC MODULUS OF BITUMINOUS MIXTURES AS RELATED TO ASPHALT TYPE

TO: J. F. McLaughlin, Director
Joint Highway Research Project

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

December 13, 1973

Project: C-36-6AA

File: 2-4-27

Attached for a JHRP research study is a Final Report titled "Dynamic Modulus of Bituminous Mixtures as Related to Asphalt Type". This research has been conducted by Mr. Larry L. Yeager, Graduate Assistant in Research on our staff, under the direction of Professor L. E. Wood of our staff. Mr. Yeager also used the Report as his thesis for the MSCE degree from Purdue University.

The primary objective of the Study was to determine a satisfactory method for evaluating the dynamic modulus of surface mixtures used by the ISHC. This determination was accomplished. A secondary objective was an attempt to correlate a physical property of the asphalt cement with the dynamic modulus. Such a correlation was established for the bituminous paving mixture used in this study.

The Report is submitted for acceptance as fulfilling the objectives of the research study.

Respectfully submitted

Harold L. Michael

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Larry L. Yeager
Graduate Assistant in Research

Joint Highway Research Project

Project No.: C-36-6AA

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Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

In cooperation with

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The Joint Highway Research Project of Purdue University who provided the funds which enabled the writer to proceed with graduate study and research.

The writer wishes to express his most sincere appreciation to Dr. Leonard E. Wood for the time and support that he continually provided in direction of this writer in completing this study.

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ABSTRACT

Yeager, Larry L. MSCE, Purdue University, December 1973. Dynamic Modulus of Bituminous Mixtures as Related to Asphalt Type. Major Professor, Leonard E. Wood.

The fundamental properties of asphaltic concrete are important to researchers as input to new design procedures being developed. The dynamic modulus of bituminous mixtures becomes a rational part of this new design procedure as a predictor of a pavement's performance in service. A review of current literature indicated that many researchers are active in determining fundamental properties of bituminous paving mixtures under a wide variety of conditions.

The main objective of this study was to determine a method for evaluating the dynamic modulus of an Indiana State Highway surface mixture. The main variables used in this study were stress level, cyclic loading rate, temperature, and asphalt type. A final procedure was developed incorporating the above mentioned variables.

Material and sample preparation included a study on compaction procedures of four by eight inch high cylindrical specimens. A compaction technique was developed that yields uniform bulk density of the four by eight inch high specimen.

A secondary objective of this study attempted to correlate a physical property of the asphalt cement to the dynamic modulus of the bituminous paving mixture.

Such a correlation was established between the dynamic modulus and the slope of the log kinematic viscosity versus $\frac{1}{\text{temperature}}$ ^{o}K plot, the cyclic loading rate, and the temperature of the test. This correlation may not be valid for mixtures using different aggregate types, gradations, and asphalt contents.

INTRODUCTION

For purposes of continuity and clarity the introduction of this paper has been divided into four separate sections:

1.) Scope

2.) Background

3.) Literature Review

4.) Statement of Problem

This particular format was chosen so that repetition of material would be held to a minimum and still be given full consideration.

Scope

This study was initiated in order to examine the extent of a correlation (if one exists) between the dynamic modulus of an asphaltic concrete mixture and some physical property of the asphaltic cement. The common practice in use today utilizes properties of the bulk asphalt and mixture parameters to design bituminous pavements. Although these methods have been adequate in the past, new technology enables one to make a better prediction of the pavements' performance when the parameter of dynamic modulus is taken into consideration. Advanced technology also contributes to complex problems when one sets out to determine the thickness design of a bituminous pavement and is unable to measure the dynamic modulus because of the lack of certain equipment necessary for its measurement. If there exists a correlation between the dynamic modulus of the bituminous paving mixture and some physical property (viscosity, ductility, penetration, etc.) of the asphalt, a simple and less complex measurement of the physical property would enable one to predict the dynamic modulus with certain precision. The thickness design of the bituminous pavement would be facilitated.

Background

The dynamic modulus of a bituminous paving mixture has been identified with numerous names by as many different investigators performing research in the area. Throughout this paper when the term "dynamic modulus" appears it will describe the relationship of a stress to strain in dynamic loading. The stress as well as the strain are time and temperature dependent which in turn indicates that the dynamic modulus depends upon:

a) loading pattern (dynamic, square wave, sine wave, etc.)

b) time of loading (frequency)

c) temperature

Shook & Kallas (1) conducted an extensive study to determine the principal factors that influence the dynamic modulus of a bituminous paving mixture. They reported the results of their study at the Association of Asphalt Paving Technologists (AAPT) meeting in 1969. No attempt was made to establish any correlation between the dynamic modulus of a bituminous paving mixture and some material property of the binder.

Heukelom and Klomp (2) made a presentation before AAPT in 1964 that verified to some extent the prediction of mixture stiffness from a measured stiffness of an asphaltic cement. Numerous others (3, 4, 5) have correlated or measured some factors that affect the dynamic modulus. Additional coverage of this area is discussed in the literature review section. Prediction of a dynamic modulus of a bituminous paving mixture from a physical property of the asphalt cement should obviously be the goal of continuing research for the determinations of factors that correlate to and influence the dynamic modulus.

Literature Review

The literature that is being written about dynamic modulus, its measurement, and factors influencing it has become voluminous. Reference to earlier authors (1 through 5) show a varied approach to both the problem and the solution.

As early as 1954 Van der Poel (6,7) demonstrated a correlation between input and response for a visco-elastic material, showing that a simple extension of Young's modulus as a solution to elastic behavior can be applied to visco-elastic materials provided certain conditions of time, temperature, and loading are met.

Monismith and Deacon (8) studied compound loading as the method of solving a design problem of bituminous pavement thickness. Others (9, 10) have investigated the relationship of a cyclic loading to a given stiffness of a mixture and have termed this relationship "dynamic response".

McLeod (11) investigated the problem of relating parameters obtained from the Marshall stability test to a value which he called the modulus of stiffness and obtained the relation:

$$M = 40 \frac{\text{stability}}{\text{flow}} \qquad 1$$

where

M = Modulus of Stiffness

Stability = Marshall stability measured in pounds

Flow = Marshall flow measured in units of .01 inch.

Bazin and Saunier (12) studied factors that influence dynamic modulus and noted that air voids have a noticable effect on stiffness modulus of dense mixes. Temperature susceptibility was also reported to have a marked influence upon stiffness modulus. The last two reports (11 and 12) are indications that there is a need to continue the research that is attempting to correlate a physical property of an asphalt cement to the dynamic modulus of a bituminous paving mixture.

Goetz (13) made use of the fundamental frequency of vibration of asphaltic concrete beams to evaluate the influence of certain mixture papameters upon a "sonic modulus". He found no consistent relationship existed between sonic modulus and asphalt content. There was an inverse relationship between temperature and sonic modulus (i.e. higher temperatures indicated a lower modulus) and between asphalt penetration and sonic modulus (i.e. again higher penetration indicates a lower modulus).

Work reported by Pagen (14) and Pagen and Ku (15), using creep tests, suggests that asphalt type as well as other mixture properties could be utilized in the prediction of time-dependent and temperature-dependent behavior of asphaltic concrete.

Heukelom and Klomp (2) and Heukelom (16) have attempted to relate mixture stiffness and bitumen stiffness.

$$\frac{S_{mix}}{S_{bit}} = \left[1 + \frac{2.5\ C_v}{n\ (1-C_v)}\right]^n \qquad 2$$

where

S_{mix} = Stiffness of mixture (modulus)

S_{bit} = Asphaltic stiffness from Van der Poel's nomograph

C_v = Vol. of aggregate (conc. of solids)

$= \frac{\text{vol. of aggregate}}{\text{vol. (agg. + asphalt)}}$

$n = .83 \log \frac{4 \times 10^5}{S_{bit}}$

(Note: 3% air voids were used and C_v = 0.7 to 0.9)

Utilizing equation (2) in conjunction with Van der Poel's nomograph, one interrelationship among mixture properties is defined that could be used to predict the dynamic modulus.

Of all of the reported studies, the efforts of Shook & Kallas (1) most closely resembles the direction of the author's investigation. However, the author intends to extend the study in the hope of establishing a correlation between the dynamic modulus of a bituminous paving mixture and a material property of the binder.

Schmidt (17) in a report presented at the Highway Research Board meeting in January 1972, predicted a resilient modulus by measurement of the deformation of a diametrally loaded specimen and obtained the relationship:

$$M_R = \frac{P\ (\mu + 0.2734)}{t\ \Delta} \qquad 3$$

where;

M_R = resilient modulus

P = load (dynamic)

μ = Poisson's ratio

t = thickness of the disk

Δ = total deformation

Values of μ of .20, .35, and .50 were used. When the value of 0.35 was used for Poisson's ratio, close correlation was found with the calculated values of M_R. Load duration of 0.1 seconds repeated twenty times each minute was used to simulate as nearly as possible the Benkleman Beam method of measuring pavement deflections. (See pages 118-162, ref. 17).

Evaluation of the fundamental relationship between stress and strain of an asphaltic paving mixture has been of great interest to many researchers (1). A form of relationship known as "complex modulus" has been researched extensively. The complex modulus is a complex number which defines the relationship between stress and strain for a linear visco-elastic material subjected to a sinusoidal loading. When a linear visco-elastic material is subjected to a loading stress of the form $\sigma = \sigma_o \sin(\omega t)$, the resulting strain response is of the form $E = E_o \sin(\omega t - \emptyset)$ which lags the stress by the phase angle, $\emptyset$. The Complex modulus E^* is defined by;

$$E^* = E' + j\,E'' \qquad 4$$

where

E^* = complex modulus

$E' = \dfrac{\sigma_o}{E_o} \cos \emptyset$

$E'' = \dfrac{\sigma_o}{E_o} \sin \emptyset$

j = imaginary number

σ_o = maximum stress applied - psi

E_o = maximum strain experienced during test - in/in.

$\emptyset$ = phase lag angle - degrees

Based on this definition the absolute value of the complex modulus, E^* , is a measure of the materials elasticity while the phase lag angle, $\emptyset$, is a measure of the viscous response.

The absolute value of the complex modulus is commonly referred to as the dynamic modulus and is defined by the equation;

$$/E^*/ = \frac{\sigma_o}{E_o} \qquad 5$$

where

$/E^*/$ = dynamic modulus - psi

σ_o = maximum stress applied - psi

E_o = maximum strain experienced during test - in/in.

The procedure for determining the dynamic modulus and the results obtained from those tests are the main concern of this research.

Shook and Kallas (1) have conducted research which most closely resembles the goals of this study except an attempt will be made to establish a correlation between the dynamic modulus and a physical property of the binder whereas Shook & Kallas (1) only listed those factors that influence the dynamic modulus.

No doubt a further search of the current literature would provide ample background, however, the concept of correlating a physical property to the dynamic modulus is still not prevalent in the literature. Investigators have primarily concerned themselves with isolating those factors which influence the dynamic modulus.

Statement of Problem

The primary objective of this study is to evaluate and select a procedure for determining the dynamic response (modulus) of Indiana State Highway. surface mixtures.

Since special equipment is currently needed to adequately evaluate dynamic modulus, a different approach to design could ensure if a correlation between physical characteristics of the asphalt cement and dynamic modulus of the asphaltic paving mixture exists.

Thus, a secondary objective of this project will be to quantify physical and rheological properties of an asphalt cement for the purpose of establishing the above mentioned correlation (if one exists) between an asphalt property and the dynamic modulus of the mixture.

MATERIAL AND SAMPLE PREPARATION

This section of the report describes all details relating to the tests performed including a description of the materials used, characterization test results, and the findings of a study concerning the best compaction procedures that would be utilized for forming four inch by eight inch cylinders of bituminous concrete.

Aggregates

Sources and Type

Aggregates for this study consist of 100 per cent crushed limestone obtained from the Pipe Creek Stone Company of Sweetser, Indiana. This producer is listed as quarry Number 162 by the Indiana State Highway Commission (18, 19).

Geologic setting for this material is the Liston Creek Limestone member (Huntington Litheface) of the Wabash formation of the Silurian period (20). A typical section of this formation contains a bluish gray to tan limestone that is cherty, fine grained, and slightly fossiliferous and usually thin bedded. It is generally accepted that the Liston Creek member is tough and can pass soundness and abrasion tests but it contains abundant chert with a specific gravity less than 2.45 (21, 22).

Preparation

Material for this study originated from the far north extremes of the quarry and received the normal commercial processing of crushing and sizing. Indiana State Highway Commission gradation sizes of 8 and 53 (23) were obtained from the producers stockpiles and transported to the Purdue Bituminous Materials Laboratories where they were re-sized to logarithmic sieve series fractions and washed.

Summary of Specification Tests and Physical Properties

Unless otherwise stated or required by standard methods, all tests were performed on each of the fractions. Results may be reported as weighted values for the gradation to be used for project mixes. The gradation chosen for this study meets the requirements of an Indiana State Highway surface mixture #9A (24) and a type IVb (25) mixture of the Asphalt Institute and is presented below.

Table 1. Sieve Analysis

Sieve	% Passing
3/4	100
1/2	82
3/8	70
4	51
8	40
16	30
30	20
50	12
100	7
200	3

Los Angeles Abrasion, (per cent wear), (ASTM):

Grading (ASTM)	Wear after 100 rev.	Wear after 500 rev.
B	7.1%	27.8%
C	6.9%	27.8%
D	8.8%	31.7%

Deleterious Materials:

A. Friable particles, ocher, and shells by visual inspection of hand specimens: None

B. Soft or nondurable particles (AASHO T189). Soft particles retained on 3/8" sieve - 3.5%

C. Chert (less than 2.45 specific gravity):

Visual count of particles that contain chert (particles may include both chert and limestone)

Size	% Chert (Count)	% Chert (wt)
3/4 - 1/2	29	29
1/2 - 3/8	22	10
3/8 - 4	16	15
4 - 8	19	14

D. Material with specific gravity less than 2.45 (bulk saturated surface dry). All material placed in heavy liquid media (1, 1, 2, 2 - Tetrabromoethane (acetylene Tetrabromide) and carbon tetrachloride; all material that floated is included in the per cent with specific gravity less than 2.45.

Size	%, by wt. with S.G. less than 2.45
3/4 - 1/2	6.4
1/2 - 3/8	6.9
3/8 - 4	6.9
4 - 8	6.0

Coarse agg. (Ret #8). % by wt. with S.G. less than 2.45 . . 6.6%

E. Specific Gravity and Absorption (ASTM C127, C128, D854).

Table 2. Specific Gravities of Individual Fractions & Test Mix

Size	G_{bulk}	G_{bssd}	G_{app}	% Abs
		Individual Fractions		
3/4 - 1/2	2.522	2.601	2.749	3.136
1/2 - 3/8	2.522	2.588	2.701	2.639
3/8 - 4	2.518	2.588	2.706	2.732
4 - 8	2.480	2.564	2.709	3.428
8 - 16	2.468	2.546	2.675	3.124
16 - 30	2.444	2.534	2.685	3.680
30 - 50	2.382	2.469	2.610	3.644
50 - 100	2.482	2.551	2.666	2.766
100 - 200	2.528	2.564	2.618	1.392
Filler	--	--	2.726	--
		Test Mix Gradation		
CA	2.518	2.588	2.708	2.788
FA	2.497	2.560	2.666	2.544

Asphalt

Three penetration grades of asphalt were used in this study;

hard asphalt - 60/70

normal asphalt - 85/100

soft asphalt - 120/150

A set of standard acceptance tests were run on each of the asphalts to characterize them. Results of these tests appear in Table 3 and typical data sheets may be seen in Appendix A.

The asphalt was produced by the American Oil Co. at the refining plant in Whiting, Indiana.

Table 3. Results of Asphalt Cement Characterization Tests

Asphalt Designation	101	102	103
Specification Tests			
Penetration 77°F, 100 gm. 5 sec.	56	85	122
Ductility 77°F, 5cm/min	100+	100+	100+
Sp. Gravity @ 77°F	1.028	1.027	1.022
Thin Film Oven Test 325°F, 5 Hrs. Penetration on Residue 77°F, 100 gm, 5 sec. % of Original	58.2	66.0	66.7
Solubility (CCl_4) Per Cent	99.6%	99.7%	99.7%
Viscosity Absolute 140°F Poise	2213	1236	678
Kinematic 275°F Cst	368	305	229
Softening Point R & B °F	129.2	121.3	113.3
P.I. (By Equation; See Appendix A)	+.03	+.06	-.008

A plot of the kinematic viscosity versus temperature for the three asphalts may be observed in Figure 1.

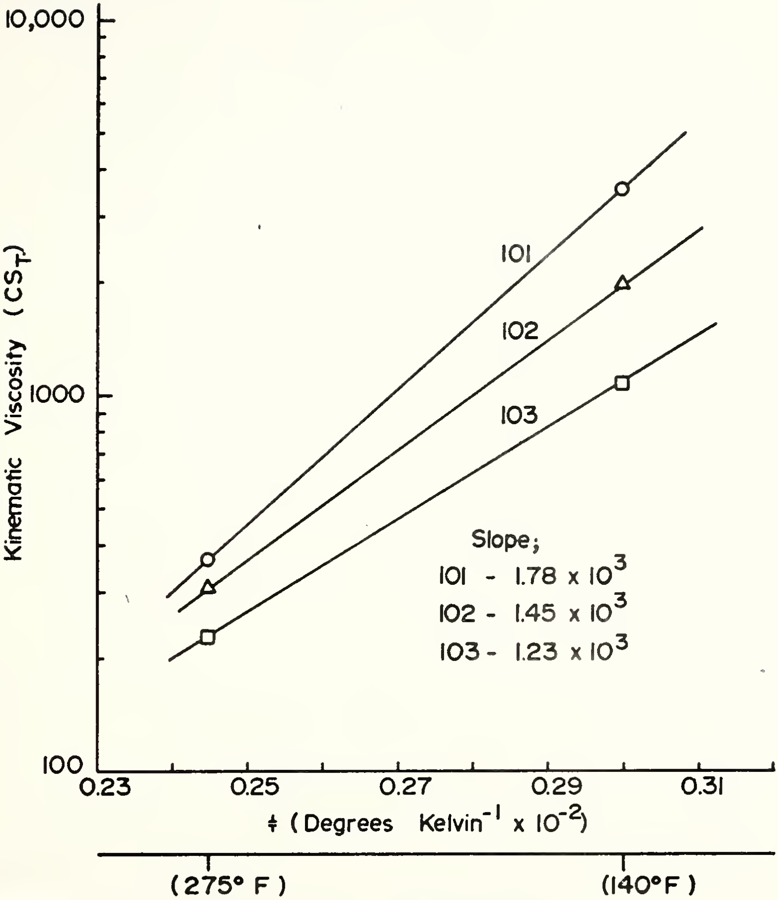

FIGURE I. RELATIONSHIP BETWEEN KINEMATIC VISCOSITY AND TEMPERATURE.

Mix Design

The Centrifuge Kerosene Equivalent method as described in Asphalt Institute Manual Series 2 was used to determine an estimated asphalt content for each of the three asphalt types.

American Society for Testing & Materials (ASTM) Designation D 1560, Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Aparatus, and ASTM Designation D1561, Preparation of Test Specimens of Bituminous Mixtures by Means of California Kneeding Compactor (26), were used to finalize the asphalt contents for the various bituminous paving mixtures included in this study. Design data and the density-voids analysis may be found in Appendix "B". Design asphalt contents for the dense graded bituminous surface paving mixture are as follows;

Dense mix - hard asphalt (101)*	A.C. = 6.7%
Dense mix - medium asphalt (102)*	A.C. = 6.5%
Dense mix - soft asphalt (103)*	A.C. = 6.3%

All asphalt contents are based on weight of dried aggregate.

*Asphalt Designation from Table 3.

Compaction Methods

Specimens for this study were prepared according to procedures given in ASTM Designation D 1561 except for certain modifications in compacted height of the specimen, specific foot pressure, and number of tamping blows.

Numerous variations of ASTM D1561 were tried so that the best method of compaction yielding the greatest uniformity could be utilized in this study. Consideration was given to foot pressure and number of blows needed to compact an eight inch specimen yet still follow as closely as possible ASTM method D1561. A summary of methods and results of these various methods follows;

Method A - ASTM D1561 was used for this method except that an eight inch high specimen was compacted rather than a two-and-one-half inch specimen. The mixture was heated to 230°F (110°C), placed in a filling trough, fed into the mold, and rodded. One-half of the material is placed into the mold and rodded forty times (twenty around the edge and twenty in the center). The other one-half is than added and rodded in the prescribed manner. A leveling type kneeding compaction at 250 psi foot pressure is applied for thirty tamps at which time the foot pressure is increased to 500 psi and applied for 150 tamps (five minutes).

Method B - ASTM D1561 was followed except for specimen height and addition of mixture to the mold. Four layers at two inches per layer were used instead of the ordinary two layer compaction method. One quarter of the total amount of mix was placed into the filling trough and then loaded into the mold. Each layer was rodded forty times (twenty around the edge and twenty in the center) and them compacted four to ten tamps with a foot pressure of 250 psi. Once the top layer was compacted at 250 psi, the higher compactive effort (500 psi) was applied for 150 tamping blows.

Method C - ASTM D1561 was used except for variations in specimen height, specific foot pressure and number of tamping blows. The mixture was placed into the filling trough and added continuously to the mold. The tamping foot was allowed to compact the mixture at 250 psi foot pressure throughout the filling process. This method of compaction causes the tamping foot to raise as more material is added thus forcing the foot to "walk-out" of the specimen mold. The entire process from start to finish takes two minutes or 60 tamping blows. Once this amount of compaction is achieved the foot pressure is increased to 500 psi and continued for 150 tamping blows. There was no rodding of the material in this method.

Method D - All of the material was introduced into the mold at one time and rodded in the usual manner (twenty times around the edge and twenty times in the center). The high compactive effort of 500 psi was placed on the specimen for a total of 200 tamping blows.

Method E - The effectiveness of the double plunger method of compaction was also studied. All of the material was placed into the mold and the double plunger method was used to compact the specimen. The load was placed on the specimen at the rate of .05" per minute, reaching an ultimate load of 1000 psi.

In all five methods tried the mixture was heated to 230°F before being compacted. A 1000 psi double plunger static load was applied at the rate of .05"/min. after the kneeding compaction was completed and the specimen cooled in a 140°F oven for 1½ hours.

After cooling was complete, the specimens were weighed in air and water and the bulk specific gravities were calculated. The specimens were then cut into eight one inch slices by means of a diamond edged masonry saw. Bulk specific gravities of the one inch slices were determined. The complete analysis of compaction technique and selection of the method to be used in this study follows;

Table 4. Results of Compaction Study

Method	Avg. Absolute Value % Variation	Standard Deviation
A	2.905%	4.98
B	2.033%	3.78
C	.998%	1.86
D	1.313%	2.24
E	2.617%	4.81

The standard deviations for the various compaction methods used were calculated from the equation;

$$S.D. = \left[\frac{1}{N-1} \quad (X_i - \bar{X})^2 \right]^{1/2} \qquad 6$$

Where:

$S.D.$ = standard deviation

N = number of slices

X_i = density of each slice

$\overline{X}$ = average density of N slices

The per cent variation was calculated from the equation;

$$\% \text{ Var.} = \frac{(\overline{X}-X_i)}{\overline{X}} \times 100 \qquad 7$$

Where

$\%$ Var. = per cent variation

X_i = density of each slice

$\overline{X}$ = average density of the N number of slices

The absolute value of the percent variation was added for each of the slices and then divided by the number of slices. This value was termed the "avg. absolute value percent variation", and appears in Table 4.

The choice of method "C" as a compaction technique was based on analysis of the data in Table 4 as well as previous investigation on techniques of compaction. Method "C" gives the best uniform bulk density throughout the specimen as well as a bulk density that closely resembles the bulk density of a 2½" compacted Hveem specimen at the design asphalt content using ASTM D1561. This fact can be seen in comparing the standard deviation values and avg. absolute value % variation values. Typical data sheets appear in Appendix C.

DYNAMIC MODULUS MEASUREMENT PROCEDURE

In the dynamic modulus tests, unconfined cylindrical specimens of a dense graded bituminous concrete surface mixture were compacted and cured in a manner previously described. The four inch diameter by eight inch high specimens were subjected to sinusoidal stresses of differing amplitudes, frequencies, and temperatures, and the resulting axial strains were studied in terms of their amplitudes and phase lag angle differences. The loading of the specimens was accomplished with a Research Incorporated, MTS Division, electric-hydraulic testing system. For the dynamic modulus tests, the sinusoidal loads were applied with the testing systems hydraulic actuator through hardened steel platform loading disks placed at either end of the specimen. A sulfur based cement compound was utilized in capping the four by eight inch cylindrical specimens to insure parallel planes of loading. A Baldwin-Lima-Hamilton (BLH) type T2G1 load cell (50,000 lb. capacity) was used to measure the loads applied. Two independent methods of measuring strain were utilized. Baldwin-Lima- Hamilton SR4 Type A-1 strain gauges were cemented vertically to the specimen at the mid-point of the 8 in. length with Bean BR 104 epoxy adhesive in accordance with manufacturer's recommended procedure.

Temperature compensation gauges were incorporated into the circuit. The output from the half-bridge strain gauge set-up was recorded by a Sanborn type 321 dual channel recorder. Duplicate strain gauge set-ups were prepared on opposite sides (180° apart) of each of the specimens and the output from each set of gauges was recorded simultaneously. An average value was determined from the duplicate gauges to calculate the strain response.

The second method of measuring strain involved the use of a linear variable differential transformer (LVDT) built into the actuator of the electric-hydraulic testing machine. The output from the LVDT as well as from the load cell was recorded using a Brush Mark 280 two-channel recorder.

Specimens were brought to test temperatures by means of a walk-in freezer (for 40°F specimens) and a forced-air oven (for 70°F & 100°F specimens). Care was taken to assure the fastest possible testing of the specimen so that only a very minimum change in temperature would occur. The temperature in the laboratory was held at a constant temperature of 70°F.

In order to determine the temperature change one might experience in testing the specimens at temper tures other than 70°F, a study of temperature change versus time was made. A four inch by eight inch high specimen was drilled in the center of the diameter and at the mid-height point. A temperature probe was placed in the hole and the specimen was brought to the test temperature (40°F or 100°F). An average of six tests gave the result that it takes 12 minutes to change the temperature one degree Fahrenheit. The testing of the specimen lasted from two to seven minutes total time.

Recorder settings, sample numbers and other needed information was placed on each trace for purposes of identification. Sample numbers were placed on specimens after capping to identify them.

There were two stress levels (50 & 100psi), three loading frequencies (1, 6 & 12 cyc/sec.), three temperatures at which tests were run (40°, 70° and 100°F), and three asphalt cements (56, 85 & 122 pen). The aggregate gradation was the same for all tests.

Table 5 summarizes the testing program for measurement of those variables needed to calculate the dynamic modulus.

Table 5. Testing Sequence

Asphalt Cement	Temp degree F.	Loading Frequency & Stress Level 1 CPS 50 psi	1 CPS 100 psi	6 CPS 50 psi	6 CPS 100 psi	12 CPS 50 psi	12 CPS 100 psi
601 (56 pen)	40	X	X	X	X	X	X
	70	X	X	X	X	X	X
	100	X	X	X	X	X	X
602 (85 pen)	40	X	X	X	X	X	X
	70	X	X	X	X	X	X
	100	X	X	X	X	X	X
603 (122 pen)	40	X	X	X	X	X	X
	70	X	X	X	X	X	X
	100	X	X	X	X	X	X

In addition to the tests performed that are listed in Table 5, two additional tests were made for a comparison basis. Soaking three speciemns for four days at 122°F allowed a test to be made that would indicate qualitatively the effect that soaking has on the dynamic modulus value.

The use of strain gauges was made in order that a comparison could be made between that type of strain measurement and use of LVDT. Consistent data was obtained for each type of strain measurement indicating that either method is equally adequate for measuring strain. Typical data sheets for calculating the dynamic modulus may be found in Appendix D. The stress strain relationship was calculated at the point in time when the amplitude of the steady state recoverable axial strain in sinusoidal loadings becomes constant. This usually was between 100 to 300 cycles.

Results of the Dynamic Modulus Test

The primary objective of this study was to evaluate and select a procedure for determining the Dynamic Modulus of Indiana State Highway surface mixtures. The results of the numerous dynamic modulus tests appear in Table 6 and are useful in fulfilling the secondary objective of this study.

The dynamic modulus measurements were made on one or two specimens at each indicated load stress level, temperature, cyclic loading rate, and asphalt type. Those tests using only one specimen were replicate tests performed using the procedure of Kallas & Riley (27) for testing specimens in replicate tests. The data taken from a dynamic modulus test may be seen on a typical data sheet in Appendix D.

The phase lag angle is not used in the dynamic modulus calculation, but is useful when calculating the complex modulus. The phase lag angles (∅) were calculated from the tests run on the specimens purely for the basis of quantitative comparison. These ∅ values appear in Table 6 with the dynamic modulus measurements.

Table 7 lists the data taken in two special test conditions. The first set of data was calculated from results of tests using SR-4 strain gauges instead of the LVTD to measure specimen deformations. In the strain gauge measurements no phase lag angle was recorded.

The second set of data was recorded for tests performed on specimens in a "soaked" condition. Each of the three specimens were placed in a water bath for four days, held at a constant temperature of 122°F. The other variables (temperature of test, cyclic rate, etc.) remained the same.

Table 6. Dynamic Modulus and Ø Values

		°F	/E*/, PSI x 10^5			Ø Phase Angle, Degrees		
Group	Load	Temp	1 cps	6 cps	12 cps	1 cps	6 cps	12 cps
601	50	40	2.000	5.714	11.441	10.8	7.2	3.4
		70	1.320	5.435	8.880	13.5	10.4	6.8
		100	0.409	3.333	8.000	19.8	15.3	10.4
602	50	40	3.300	8.649	10.684	18.0	8.6	5.6
		70	2.445	5.721	8.880	23.4	13.8	9.3
		100	0.297	3.000	7.280	28.8	19.3	13.8
603	50	40	3.400	8.000	9.158	19.4	12.4	7.2
		70	2.927	5.530	8.880	26.9	20.1	15.3
		100	0.306	3.250	8.000	30.4	27.8	19.6
601	100	40	3.204	6.163	10.666	16.4	14.3	12.6
		70	2.265	5.917	8.880	21.6	20.1	15.7
		100	1.250	4.500	7.596	26.6	21.4	21.0
602	100	40	4.105	6.660	10.666	19.4	15.5	13.4
		70	2.680	5.570	8.880	26.3	20.8	17.8
		100	0.903	4.306	7.958	28.1	25.3	24.0
603	100	40	4.567	6.538	10.666	23.9	20.1	15.7
		70	2.320	5.319	8.880	29.8	28.4	21.6
		100	1.004	4.459	8.000	36.5	34.3	35.0

Table 7. Dynamic Modulus of Special Tests

Group	Load (psi)	Temp	Frequency (cps)	$/E^*/$, psi x 10^5	Ø
601*	50	70	1	1.645	--
602*	50	70	1	2.083	--
603*	50	70	1	3.333	--
601**	50	70	1	.400	18.0°
602**	50	70	1	.400	21.6°
603**	50	70	1	.349	18.8°

* Strain Gauge Measurement

** Soaked Specimens (4 days @ 122°F.) LVDT measurement

Typical data sheets and traces of the test load and deformation recorded on the chart recorder appear in Appendix D.

Test data appears in Figures 2-7 and shows the relationship of the $\mathrm{Log}_{10}\mathrm{Log}_{10}$ (dynamic modulus) versus Log_{10} (loading frequency). The dynamic modulus is measured in psi and the loading frequency is in cycles/sec. Each graph is plotted at one load stress level and for one asphalt type. The three lines represent the relationship between $\mathrm{Log}_{10}\mathrm{Log}_{10}$ (dynamic modulus) and Log_{10} (frequency) at one, six and twelve cps for temperatures of 40°, 70°, and 100°F. The "least-squares fit" was used in plotting the data.

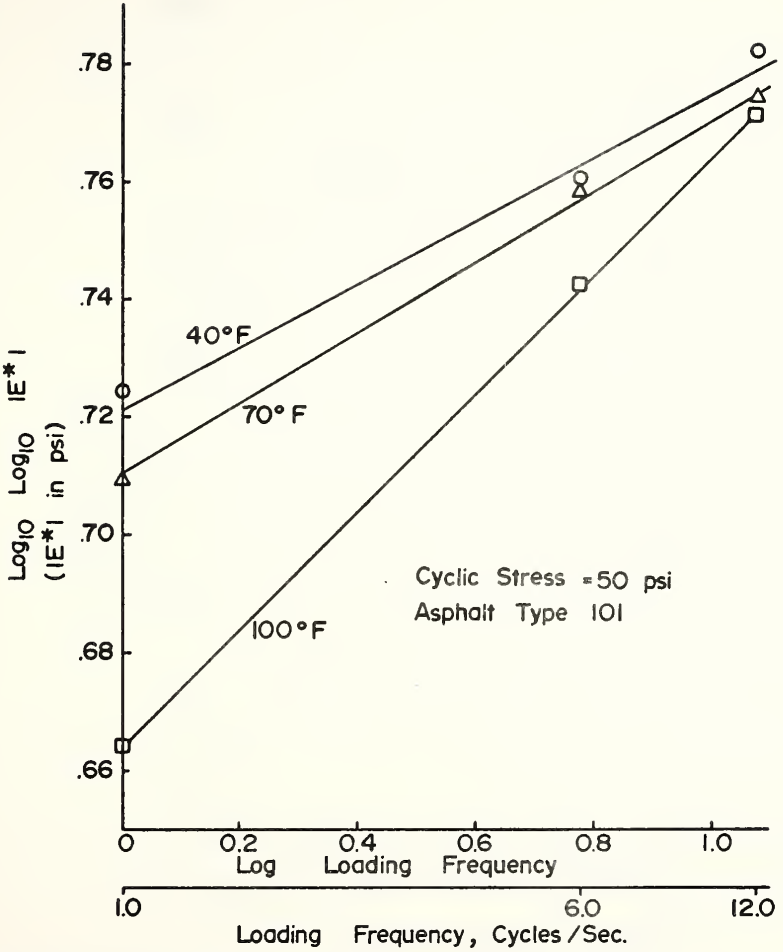

FIGURE 2. RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

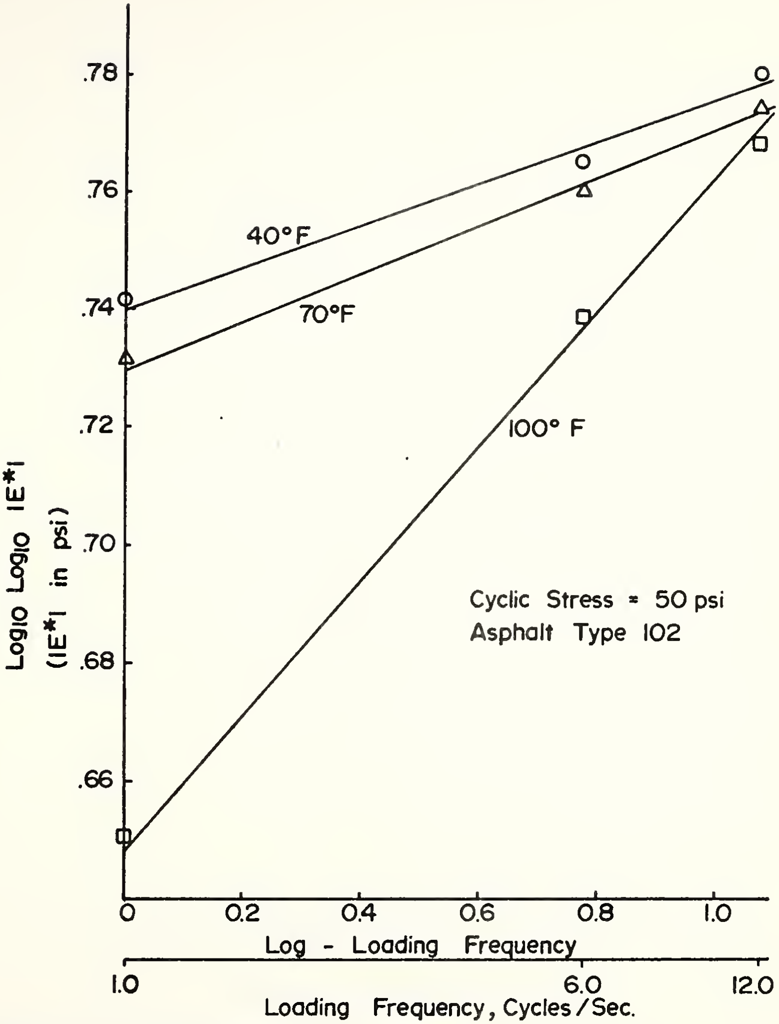

FIGURE 3 RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

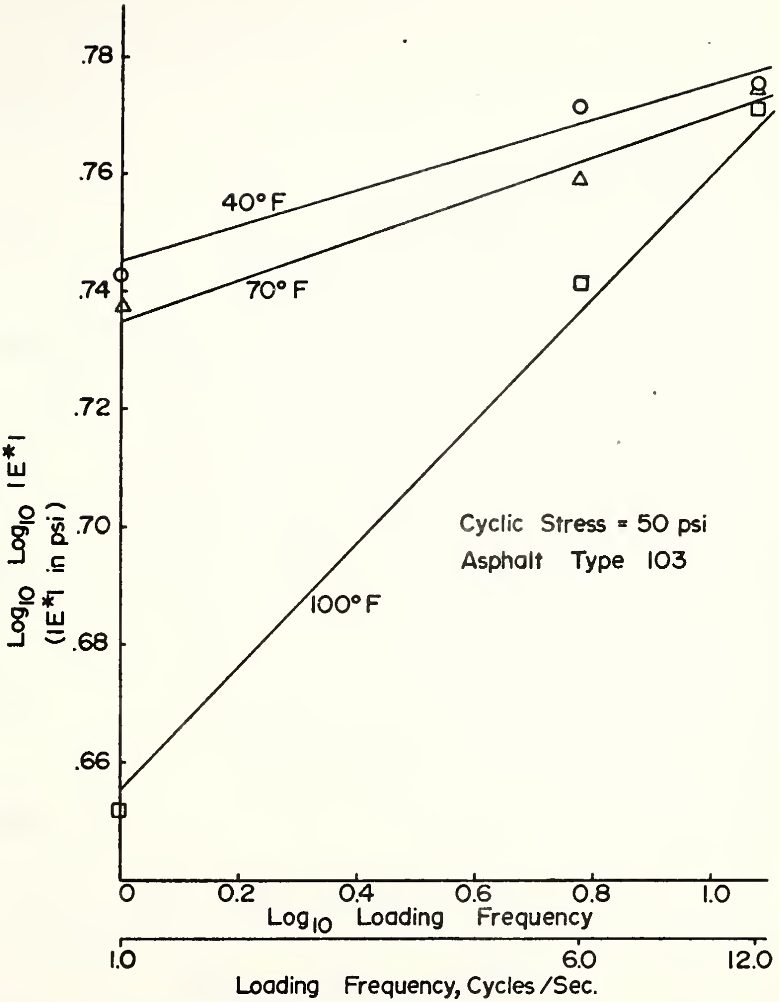

FIGURE 4 RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

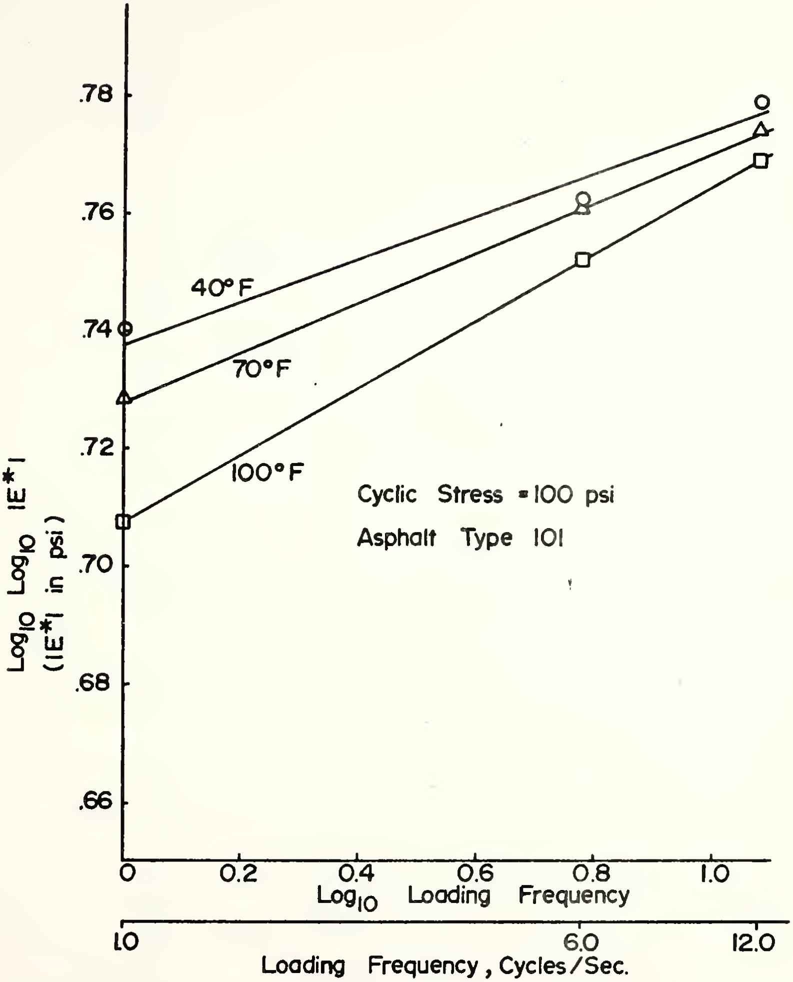

FIGURE 5 RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

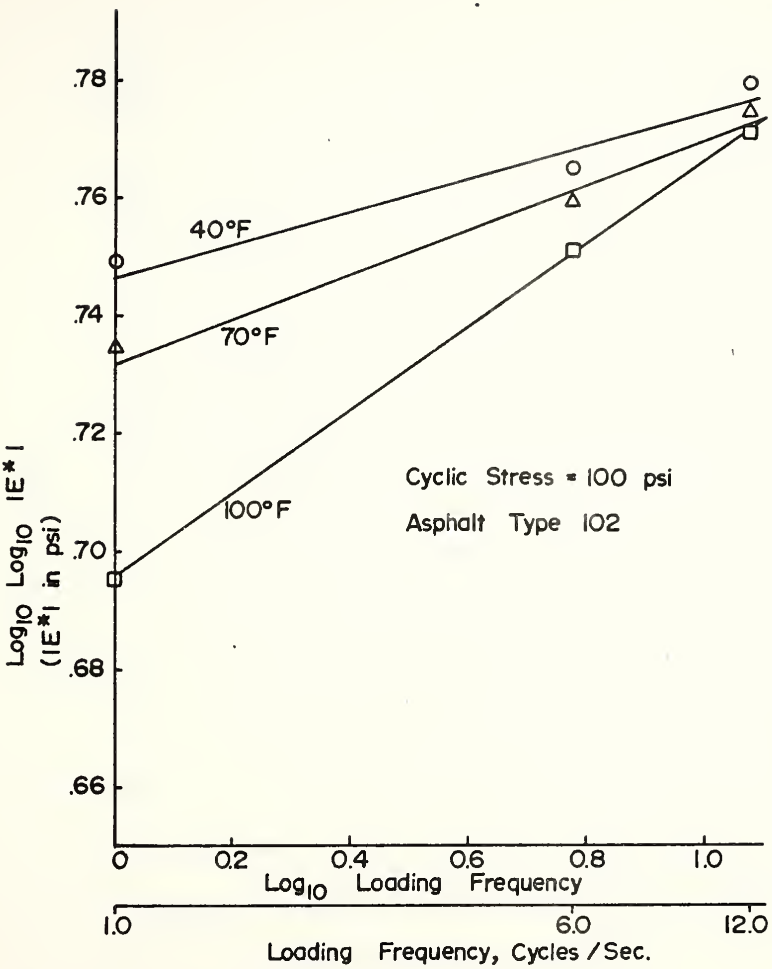

FIGURE 6 RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

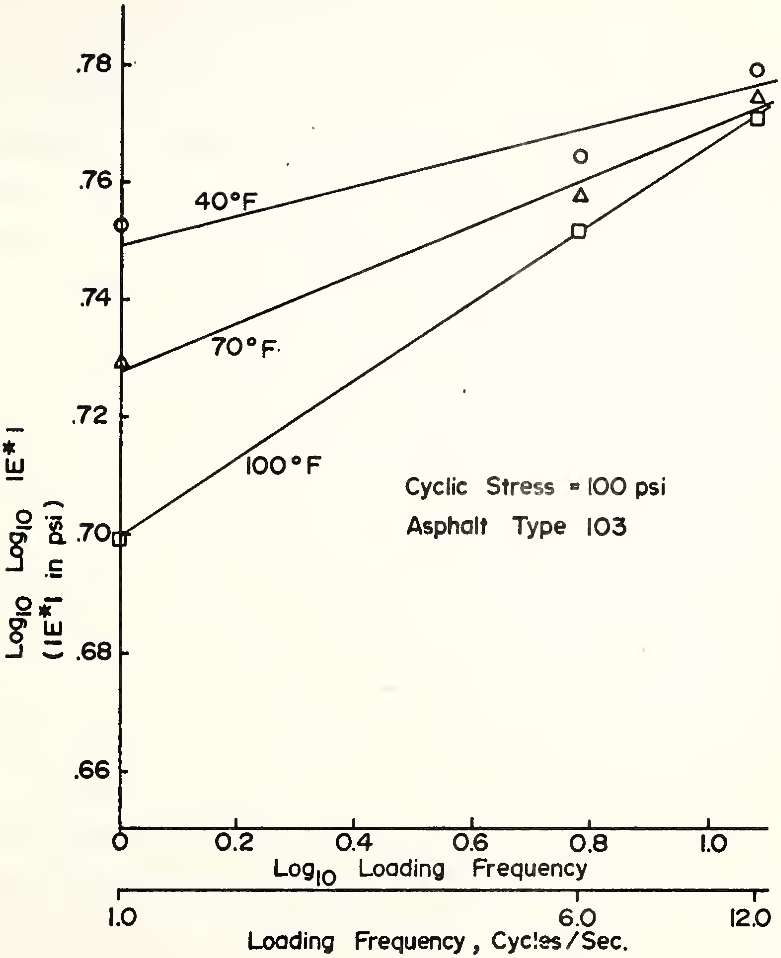

FIGURE 7. RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

DISCUSSION OF RESULTS

The fundamental objective of this study was to establish a procedure for determining the dynamic modulus of a bituminous paving mixture. In order to accomplish this objective it was necessary to determine the influence of certain variables upon the dynamic modulus. The four variables investigated were temperature, frequency of load application, stress level, and asphalt type. Discussion concerning the influence of these variables is covered in the section entitled "Influence of Certain Variables upon the Dynamic Modulus of Paving Mixtures."

A secondary objective of this study was to establish a correlation between a property of the asphalt cement and the dynamic modulus of an asphalt paving mixture. The discussion of this material is covered in the section entitled "Establishment of a Correlation Between Dynamic Modulus and a Property of the Asphalt".

A limited study concerning the influence of moisture on the dynamic modulus of asphaltic paving mixtures is discussed in the section entitled "Effect of Moisture Upon Dynamic Modulus."

Influence of Certain Variables Upon The Dynamic Modulus of Paving Mixtures

The values of the dynamic modulus may be influenced by a number of variables. The following four controlled test variables are discussed and summarized in this section: temperature, frequency, stress level, and asphalt type.

Temperature

The dynamic modulus, /E*/ and phase lag angle, Ø are a function of the temperature at which the test is performed. Figures 2 through 7 indicate for a given set of conditions that the dynamic modulus value decreases with an increase in temperature. For a stress level of 50 psi and loading rate of 1 cycle/sec. (See Fig. 2) the modulus decreases from $2.00\text{x}10^5$ psi at 40°F to $0.409\text{x}10^5$ psi at 100°F. Similar results may be seen at other stress levels, cyclic loading rates and asphalt types. At twelve cycles per second and a load stress level of 50 psi the value of the dynamic modulus varied from $11.441\text{x}10^5$ psi for 40°F to $8.00\text{x}10^5$ psi for 100°F.

In all cases of loading, cyclic rate, and asphalt type; the trend of realizing a higher dynamic modulus value at a lower temperature was not unexpected because of the viscoelastic character of the bituminous paving mixture.

Frequency

The variation of the dynamic modulus value with the frequency of load application is a basic property of an asphaltic concrete mixture. The response (in this case the dynamic modulus) of a viscoelastic mixture depends directly upon the time of loading and the temperature at which the test is made. Similar results of the dynamic modulus value may be obtained at two different temperatures by simply changing the rate of loading at one of the temperatures. This is known as the time-temperature superposition principle (28). The frequency of load application to a viscoelastic material has a direct effect upon the response.

A rapid frequency of loading (12 cps) does not allow the specimen enough time to flow and thus the specimen acts more elastically. Slower rates of loading (1 cps) allow the specimens to flow which in turn yields a larger total strain. The modulus value becomes less at the slower rates of loading because of the larger total strain.

For a stress level of 50 psi, a temperature of 40°F, and asphalt type 101, the modulus value increases from 2.00×10^5 psi to 11.441×10^5 psi as the rate of loading increases from one to twelve cycles per second.

All asphalt types, stress levels and temperatures gave similar results of an increase in dynamic modulus value with an increase in cyclic rate, as can be seen in Figures 2-7. The trend of an increase in dynamic modulus value with an increase in frequency of loading was not unexpected because of the viscoelastic character of the bituminous paving mixture.

The importance of frequency has already been established. The range of frequencies used in this study can be related to studies that correlate vehicle speed to frequency of load application. Coffman (29) concluded that a vehicle acts as a cyclic load with a wave length of six feet. Knowing this allows one to relate vehicle speed to test frequencies using the equation;

$$V = f\lambda \qquad 8$$

where;

V = velocity (ft/sec)

f = frequency (sec^{-1})

λ = wave length of a car (ft)

Using the above relationship, the loading frequencies of 1, 6, and 12 cycles per second used in this study represented speeds of 5, 25, and 50 miles per hour respectively.

Stress Level

By definition, a linear material is one whose stress-strain ratio (a modulus value) is independent of the level of stress applied. It is commonly accepted that an asphaltic concrete mixture is not a linear material. However, it is possible to characterize an asphaltic concrete mixture at low stress levels when its behavior approximates that of a linear material. Stress levels of 50 and 100 psi were chosen for this study to approximate tire pressures experienced by the pavement in service. It is accepted by many researchers that linear results of the dynamic modulus test may be obtained in total compression tests up to a maximum value of 70 psi for temperatures of 40, 70, and 100°F. It can be seen in Table 5 that for temperatures, asphalt contents and cyclic loading rates, the dynamic modulus values are similar at 50 and 100 psi, with exception occurring when one uses a cyclic stress of 100 psi at the extreme conditions of temperature (100°F)and loading rate (1 cps).

Asphalt Type

The classic response one would expect concerning asphalt type and dynamic modulus is that the higher penetration asphalts used in an asphaltic concrete mixture tend to lower the dynamic modulus, all other factors remaining the same. The dynamic modulus values recorded for the three asphalt types 101, 102, and 103 are $2.0\text{x}10^5$, $3.3\text{x}10^5$, and $3.4\text{x}10^5$ psi for tests conducted at 40°F, 1cps, and 50 psi. The dynamic modulus values recorded for other test levels compare with the ordering of the above values for differing sets of conditions.

Establishment of a Correlation Between Dynamic Modulus and a Property of the Asphalt

A secondary objective of this study was to establish if possible a correlation between the dynamic modulus and some physical property of the asphalt cement. The slope of the log kinematic viscosity versus $1/T^{o}K$ curve for the asphalt cements was chosen as the index to quantify the various binders. The temperature at which the dynamic modulus test was conducted and the frequency of loading were two other variables that were incorporated into the correlation equation. The form of the equation is:

$$\log /E^*/ = \log (x_1)(x_2) + x_3 \qquad 9$$

where

$/E^*/$ = Dynamic Modulus

x_1 = slope of log kinematic viscosity versus $1/T^{o}K$ curve

x_2 = $\log T - \dfrac{\log T - \log 40}{.710}$

x_3 = log (frequency of loading in cycles/sec)

T = temperature at which test will be made in °F.

These variables were selected on the basis that they affected the dynamic modulus more significantly in this study than any of the other variables. The variables represent a viscous character, a temperature, and a loading rate. Other variables may affect the dynamic modulus in a pronounced manner but were not included within the scope of this study.

Table 8. Calculated Values and Experimental Values of Dynamic Modulus

			Log_{10} /E*/x10^5 psi Experimental	Log_{10} /E*/x10^5 psi Calculated
	40F	1	5.301	5.206
		6	5.757	5.945
Sample 601		12	6.058	6.285
	70F	1	5.120	4.884
50 psi		6	5.735	5.662
		12	5.948	5.963
	100F	1	4.612	4.680
		6	5.522	5.458
		12	5.903	5.759

Table 8 lists the various values of the dynamic modulus from the experimental tests as well as those values calculated from equation . The comparison in Table 8 is for asphalt type 101, tested at a stress level of 50 psi and for temperatures of 40°, 70°, and 100°F and

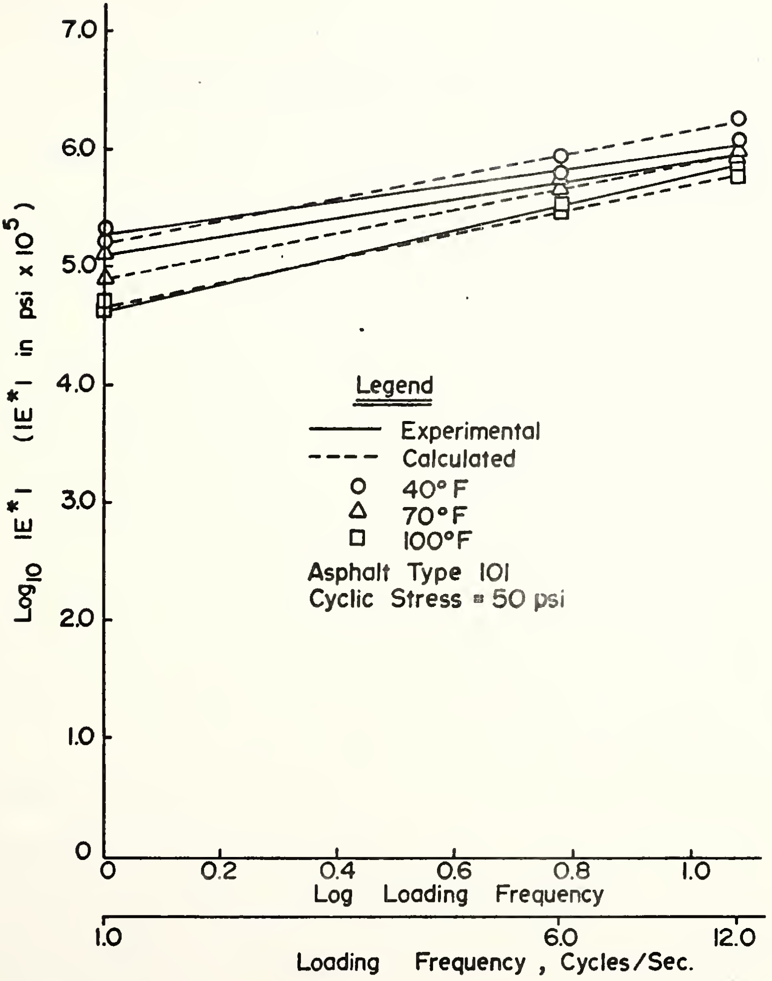

FIGURE 8. RELATIONSHIP BETWEEN CALCULATED VALUES OF DYNAMIC MODULUS PLOTTED WITH EXPERIMENTAL VALUES AND CYCLIC LOADING RATE.

cyclic loading rates of 1, 6, and 12 cycles per second. A comparison of the experimental and calculated values of the $\log_{10} /E^*/$ versus the $\log_{10}$ loading frequency may be seen in Figure 8. Closest correlation may be seen for this particular data at 1, 6, and 12 cps at 100°F.

Effect of Moisture on Dynamic Modulus

The effect of moisture due to field exposure upon the dynamic modulus of bituminous mixtures could be of importance to the flexible pavement designer. It was the intent of this limited study to determine the effect of moisture on dynamic modulus values. The method used to expose the mixtures to moisture was to soak the specimens for four days in a water bath at 122°F. The dynamic modulus values for the unsoaked condition at 70°F, 50 psi, and 1 cycle per second (taken from Table 6) are 1.32×10^5 psi for group 601, 2.445×10^5 psi for group 602, and 2.927×10^5 psi for group 603. The dynamic modulus values for the soaked specimens at the same test conditions as previously listed are $.40 \times 10^5$ psi for group 601, $.40 \times 10^5$ psi for group 602, and $.349 \times 10^5$ psi for group 603 (values are from Table 7). As may be noted from Table 7 the three values listed for the soaked specimens are considerably less than those values of the dynamic modulus in the unsoaked condition. This reduction is probably a function of the aggregate type as well as gradation, asphalt content and type. However, the reduction in the dynamic modulus value of a soaked specimen is significant and could be of great importance to the flexible pavement designer if it could be correlated to field exposure.

A RECOMMENDED PROCEDURE FOR DETERMINING THE DYNAMIC MODULUS OF INDIANA STATE HIGHWAY SURFACE MIXTURES

A testing device capable of measuring small strains and recording load and deformation simultaneously is essential to determining the dynamic modulus of an asphaltic concrete mixture. A Research Incorporated, MTS Division, electro-hudraulic testing machine with a Bruch Mark 280 dual channel recorder is widely used in the area of dynamic modulus measurements.

A compaction technique for four by eight inch high specimens that yields uniform bulk density throughout the specimen is very important in the dynamic modulus measurement test. Such a technique has been developed by this investigator and is recommended for compaction of four by eight inch high specimens of Indiana State Highway surface mixtures. The compaction technique consists of following ASTM D 1561 except for variations in specimen height, specific foot pressure, and number of tamping blows. The mixture is placed into the filling trough and added continously to the mold. The tamping foot is allowed to compact the mixture at 250 psi foot pressure throughout the filling process. This method of compaction causes the tamping foot to raise as more material is added thus forcing the foot to "walk-out" of the specimen mold. The entire process from start to finish takes two minutes or 60 tamping blows. Once this amount of compaction is achieved the foot pressure is increased to 500 psi and continued for five minutes or 150 tamping blows. There is no rodding of the material in this method. The molded specimen is then placed in a 140°F oven for one and one-half hours at which time a 1000 psi double plunger static load is applied at the rate of .05"/min.

The number of specimens needed to evaluate the dynamic modulus depends on the number of variables being considered. There should be one specimen for each combination of variables, These specimens may be tested twice at the same conditions thus creating replicate specimen results which are acceptable in this type of test.

Stress level is a less important variable to consider because of the linear relationship between dynamic modulus and a reasonable stress level. For this reason a single stress level of 50 psi is recommended because it tends to simulate the pattern of traffic on an asphaltic pavement.

Temperature and rate of loading are the two most important variables of the dynamic modulus test. Therefore it is recommended that three rates of loading and three temperatures be utilized in a test program. The three rates of loading recommended are 1, 6, and 12 cycles per second which is equivalent to speeds of .5, 25, and 50 miles per hour respectively and closely resembles speeds experienced on many bituminous pavements. (See page 37, equation 8.) Three temperatures of 40°F, 70°F, and 100°F are recommended to include the variation of temperatures experienced by a bituminous pavement in service. However, these temperatures do not cover the entire range of temperatures experienced in the field but are those temperatures attainable in laboratory testing.

CONCLUSIONS AND SUMMARY

The main objective of this study was to develop a procedure for determining the dynamic modulus of an Indiana State Highway surface mixture. Within the framework of this study which was limited to a specific aggregate type, gradation, asphalt type and asphalt content, the following conclusions seem warranted;

a) Dynamic modulus increases with an increase in the frequency of load application.

b) Dynamic modulus decreases with an increase in temperature for a given cyclic loading rate, asphalt type, and stress level.

c) The following relationship was developed between the dynamic modulus of an Indiana State Highway surface mixture and certain variables (temperature, loading rate, a function of original asphalt viscosity vs temperature plot),

$$\text{Log } /E^*/ = \text{Log } (x_1)\ (x_2) + x_3$$

d) Soaking a four by eight inch high specimen for four days in a 122°F water bath reduces markedly the dynamic modulus value for the particular aggregate type used in this study.

e) A stress level of 100 psi at the extreme conditions of temperature (100°F) and cyclic rate (1 cycle per second) resulted in non-linear values of dynamic modulus.

f) Varying the asphalt type used in the bituminous surface mixtures of this study had a marked influence on the dynamic modulus values. However, the different asphalt types used in this study were mixed at different asphalt contents and could have affected the observed differences.

Summary

Dynamic modulus and other variables from an Indiana State Highway surface mixture were used to develop a relationship between dynamic modulus and certain variables. A procedure was developed to determine the dynamic modulus of an Indiana State Highway surface mixture. A compaction technique was devised such that four by eight inch high specimens of bituminous concrete had a uniform density throughout.

SUGGESTIONS FOR FUTURE RESEARCH

Future studies in the area of dynamic modulus measurements and relationships to properties are listed below:

a) The dynamic modulus of the original asphalt should be determined. This value could possible be used in a correlation equation that would attempt to relate this particular physical characteristic of the asphalt to the dynamic modulus value of the bituminous paving mixture.

b) An evaluation of the dynamic modulus of Indiana State Highway surface mixtures using different asphalt contents at constant mixture densities or using a fixed asphalt content while varying densities could be performed. No attempt was made in this study to quantify the effect of asphalt content on the dynamic modulus.

c) The influence of different types of mineral filler could be measured to determine the role a filled bitumen has on the dynamic modulus value of Indiana State Highway surface mixtures.

d) The effect of moisture on the dynamic modulus of bituminous paving mixtures could be quantified to simulate field moisture conditions. This type of information could be useful in more realistically designing flexible systems.

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APPENDICES

Appendix A

101 $SP_{R\&B} = 54.0^{\circ}C\ (129.2^{\circ}F)$

$$PTS = \frac{\log 800 - \log Pen\ 77^{\circ}F}{S.P._{R\&B} - 77^{\circ}F}$$

$$= \frac{2.903 - 1.748}{129.2 - 77.0}$$

$$= .0221$$

$$PI = \frac{30}{1 + 90\ PTS} - 10$$

$$= \frac{30}{1 + 90(.0221)} - 10$$

$$PI = + .03$$

102 $SP_{R\&B} = 49.6^{\circ}C\ (121.3^{\circ}F)$

$$PTS = \frac{\log 800 - \log Pen\ 77^{\circ}F}{SP_{R\&B} - 77^{\circ}F}$$

$$= \frac{2.903 - 1.929}{121.3 - 77}$$

$$= .0220$$

$$PI = \frac{30}{1 + 90\ PTS} - 10$$

$$= \frac{30}{1 + 90(.0220)} - 10$$

$$= + .06$$

103 $SP_{R\&B} = 45.2^{\circ}C\ (113.3^{\circ}F)$

$$PTS = \frac{\log 800 - \log Pen\ 77^{\circ}F}{SP_{R\&B} - 77^{\circ}F}$$

$$= \frac{2.903 - 2.086}{113.3 - 77.0}$$

$$= .0225$$

$$PI = \frac{30}{1 + 90\ PTS} - 10$$

$$= \frac{30}{1 + 90(.0225)} - 10$$

$$= -.008$$

Appendix B

Table 1A. HVEEM MIX DESIGN

Dense Graded Mix 1200 gm.

Size	Tot % Pass	Tot % Ret	Ret on Sieve	wt. Ret.	Com wt. Ret
3/4 - 1/2	100	0	18	216	216
1/2 - 3/8	82	18	12	144	360
3/8 - 4	70	30	19	228	588
4 - 8	51	49	11	132	720
8 - 16	40	60	10	120	840
16 - 30	30	70	10	120	960
30 - 50	20	80	8	96	1056
50 - 100	12	88	5	60	1116
100 - 200	7	93	4	48	1164
Filler	3	97	3	36	1200

Mix	Bitumen Ratio by CKE	% Asphalt Cement to be evaluated by Hveem Stabilometer
601 (60/70)	5.9	5.4, 5.9, 6.4, 6.9
602 (85/100)	5.7	5.2, 5.7, 6.2, 6.7
603 (120/150)	5.5	5.0, 5.5, 6.0, 6.5

Table 2A. Typical Mix Design Data

Trial Mix Series: 603 Sp. Gr. AC 1.022 Lab. No. for AC Used: 103

Agg. Used: Marion K_f=1.45 K_c=1.5 K_m - 1.43 Total SA 22.5 Sq.Ft./Lb

Estimated % AC using CKE Tests only 5.5 AC

Recommended % AC using Mix Design Criteria 6.3 AC

Specimen Identification	A	B	C	D
% AC by Wgt of Agg.	5.0	5.5	6.0	6.5
Wgt. in Air-grams	1242.4	1244.7	1246.3	1249.2
Wgt. in Water-grams	698.6	692.6	708.1	709.5
Bulk Volumn-cc	554.4	557.1	546.8	547.1
Bulk Density	2.240	2.234	2.279	2.283
Max Theor. Density	151.25	151.25	151.25	151.25
% Voids - Total Mix	7.3	7.5	5.7	5.5
Unit Wgt. - pcf.	139.77	139.40	142.20	142.45

Total Load-lbs.	Unit Load-psi	Stabilometer			
500	40	10	12	13	9
1000	80	13	17	17	13
2000	160	18	22	23	18
3000	240	24	28	28	24
4000	320	31	33	34	31
5000	400	38	40	42	41
6000	480	46	49	50	54
Displacement-turns		3.14	3.00	3.11	3.07
Corr. Stability Value		47.0	44.0	44.0	43.0

Table 2A, cont.

Cohesiometer

Temperature - °F.	140	140	140
Effective Height-in.	2.75	2.75	2.75
Shot Weight - grams	413.2	336.2	307.4
Cohesiometer Value	116.9	95.1	86.9

G_{mm} = 2.416

Table 3A. Density-Voids Analysis

Rice

A - 1997.7; B = 1984.8

Sample	Flask	Wt. Empty	Flask+ Sample	Wt. Sample	Flask+ Sample+ H_2O	G_{mm}
603A	A	938.4	1457.4	519.0	2302.1	2.419
603B	B	909.7	1624.4	714.7	2405.4	2.430
602A	A	846.6	1425.3	578.7	2334.4	2.391
602B	B	817.9	1479.9	662.0	2374.7	2.432
601A	A	846.4	1436.9	590.5	2342.8	2.406
601B	B	817.6	1455.4	637.8	2359.7	2.426

Sample	100 G_{mm}	Ptac	Ptac/Gac	Pag	G_v	G_b
603A	41.339	5.21	5.093	94.79	2.615	2.225
603B	41.152	5.21	5.093	94.79	2.628	2.225
602A	41.823	5.39	5.248	94.61	2.588	2.219
602B	41.118	5.39	5.248	94.61	2.638	2.219
601A	41.562	5.57	5.418	94.59	2.617	2.247
601B	41.220	5.57	5.418	94.59	2.642	2.247

G_v (avg)

601 - 2.625

602 - 2.663

603 - 2.622

Table 3A, Cont.

Absorbed Asphalt:

$$A_{ac} = \frac{G_v - G_{ag}}{G_v\ G_{ag}} \quad 100\ G_{ac}$$

Sample	G_v	G_{ag}	A_{ac}
601	2.625	2.507	1.84
602	2.663	2.507	2.39
603	2.622	2.507	1.78

Effective Asphalt:

$$P_{eac} = P_{tac} - \frac{A_{ac}}{100} \quad P_{ag}$$

Sample	P_{tac}	P_{ag}	P_{eac}
601	5.57	94.59	3.83%
602	5.39	94.61	3.13%
603	5.21	94.79	3.53%

Voids:

$$V_v = 100 - P_{gm}$$

Sample	V_v
601	5.2%
602	5.3%
603	5.4%

$$VMA = 100 - \frac{P_{ag}\ G_{mb}}{G_{ag}}$$

Sample	V.M.A.
601	13.79%
602	13.85%
603	13.75%

Appendix C. Table 4A. Compaction Study, Method A

Slice	Position	Dry Wt (gm)	S.S.D. Wt (gm)	Wet Wt (gm)	Vol. (cm^3)	Sp. Gr.	Density ($\#/ft^3$)
1	Top	432.9	440.6	254.1	205.7	2.321	144.83
2		398.0	403.0	227.4	180.0	2.267	141.46
3		397.5	402.7	224.3	205.7	2.228	139.02
4		348.9	353.4	198.8	167.2	2.258	140.89
5		371.5	375.2	202.6	180.0	2.108	131.53
6		373.7	379.8	203.6	192.6	2.121	132.35
7		323.7	328.0	180.9	154.3	2.200	137.28
8		479.7	483.8	257.2	244.4	2.117	132.10

Avg. 8 Slices = 137.43 Bulk Density 8" Compacted Specimen = 138.18

Variation from Avg.

$$\% \text{ Variation} = \frac{(\bar{x}-x_i)}{\bar{x}} \times 100$$

Slice	Density	% Variation
1	144.83	+4.65%
2	141.46	+2.93%
3	139.02	+1.16%
4	140.89	+2.52%
5	131.53	-4.29%
6	132.35	-3.70%
7	137.28	- .11%
8	132.10	-3.88%

Notes: It seems as though the deeper one goes toward the bottom of the specimen the less compaction one gets. A more uniform variation would be desired.

Table 5A. Compaction Study, Method B

Slice	Position	Dry Wt (gm)	S.S.D. Wt (gm)	Wet Wt (gm)	Vol. (cm^3)	Sp. Gr.	Density (#/ft^3)
1	Top	434.9	438.8	249.1	189.7	2.292	143.02
2		432.9	436.3	244.8	191.5	2.260	141.02
3		375.2	379.3	207.3	172.0	2.181	136.09
4		364.5	369.8	203.1	166.7	2.187	136.47
5		306.2	310.3	164.6	145.7	2.102	131.16
6		353.8	357.5	194.1	163.4	2.165	135.09
7		471.3	475.6	261.9	213.7	2.205	137.60
8	Bottom	426.5	431.1	232.7	198.4	2.150	134.16

Avg. 8 Slices = 136.83

Bulk Density 8" Compacted Specimen = 138.33

Variation from Avg.

$$\% \text{ Variation} = \frac{(\bar{x}-x_1)}{\bar{x}} \times 100$$

Slice	Density	% Variation
1	143.02	+4.52%
2	141.02	+3.06%
3	136.09	- .54%
4	136.47	- .26%
5	131.16	-4.14%
6	135.09	-1.27%
7	137.60	+ .53%
8	134.16	-1.95%

Notes: The scatter in the variation shows lack of uniformity and a poor compaction technique.

Table 6A. Compaction Study, Method C

Slice	Position	Dry Wt (gm)	S.S.D. Wt (gm)	Wet Wt (gm)	Vol. (cm^3)	Sp. Gr.	Density ($\#/ft^3$)
1	Top	470.7	476.8	271.0	205.8	2.287	142.71
2		459.3	465.5	265.6	199.9	2.297	143.33
3*		315.3	320.4	177.8	142.6	2.211	137.96
4		418.3	423.7	239.9	183.8	2.276	142.02
5		410.3	415.6	234.7	180.9	2.268	141.52
6		412.9	417.3	235.4	181.9	2.294	143.14
7		382.7	388.3	221.8	166.5	2.298	143.39
8	Bottom	400.9	405.0	226.9	178.1	2.251	140.46

*Bad Specimen--Lost Material

Avg. 8 Slices = 141.82 Bulk Density 8" Compacted Specimen = 141.82

Variation from Avg.

% Variation = $\frac{(\bar{x}-x_1)}{\bar{x}}$ x 100

Slice	Density	% Variation
1	142.71	+ .89%
2	143.33	+1.06%
3	137.96	-2.72%
4	142.02	+ .14%
5	141.52	- .21%
6	143.14	+ .92%
7	143.39	+1.10%
8	140.46	- .95%

Notes: Except for the one bad specimen, there seems to be a fairly good uniformity in this procedure.

Table 7A. Compaction Study, Method D

Slice	Position	Dry Wt (gm)	S.S.D. Wt (gm)	Wet Wt (gm)	Vol. (cm^3)	Sp. Gr.	Density (#/ft^3)
1	Top	472.7	479.3	273.5	205.8	2.297	143.33
2		353.6	356.7	196.7	160.0	2.210	137.90
3		435.8	441.6	251.2	190.4	2.289	142.83
4		393.0	397.8	220.4	177.4	2.215	138.21
5		366.3	371.9	205.5	166.4	2.201	137.34
6		420.5	426.6	238.8	187.8	2.239	139.71
7		402.1	409.6	231.8	177.8	2.262	141.14
8	Bottom	410.5	414.7	232.6	182.1	2.254	140.64

Avg. 8 Slices = 140.14   Bulk Density 8" Compacted Specimen = 139.52

Variation from Avg.

$$\% \text{ Variation} = \frac{(\bar{x}-x_1)}{\bar{x}} \times 100$$

Slice	Density	% Variation
1	143.33	+2.28%
2	137.90	-1.60%
3	142.83	+1.92%
4	138.21	-1.37%
5	137.34	-1.99%
6	139.71	- .30%
7	141.14	+ .71%
8	140.64	+ .34%

Notes: Although there seems to be more consistency in the variation from the average, these values are quite high.

Table 8A. Compaction Study, Method E

Slice	Position	Dry Wt (gm)	S.S.D. Wt (gm)	Wet Wt (gm)	Vol. (cm^3)	Sp. Gr.	Density ($\#/ft^3$)
1	Top	400.7	405.7	221.8	183.9	2.179	135.96
2		352.1	354.9	193.4	161.5	2.180	136.03
3		361.0	363.4	195.2	168.2	2.146	133.91
4		418.4	422.4	242.3	180.1	2.323	144.95
5		347.6	350.1	194.6	155.1	2.235	139.46
6		435.1	438.6	253.6	185.0	2.352	146.76
7		455.1	459.0	254.9	204.1	2.230	139.15
8*	Bottom						

*Specimen was not high enough for eight slices.

Avg. 7 Slices - 139.46 Bulk Density 7" Compacted Specimen = 137.86

Variation from Avg.

$$\% \text{ Variation} = \frac{(\bar{x}-x_1)}{\bar{x}} \times 100$$

Slice	Density	% Variation
1	135.96	-2.51%
2	136.03	-2.45%
3	133.91	-3.98%
4	144.95	+3.93%
5	139.46	0.00%
6	146.76	+5.23%
7	139.15	- .22%

Notes: The scatter for this method indicates that the compaction isn't uniform and that the compaction does not even come close to a 95% compaction of maximum theoretical.

Table 9A. Calculated Standard Deviations of

Eight Inch Compacted Specimens

$$SD = \left[\frac{1}{N-1} \quad (x_1 - \bar{x})^2 \right]^{\frac{1}{2}}$$

Slice	Density	$\left[x_i - \bar{x}\right]$	$\left[x_i - \bar{x}\right]^2$	Slice	Density	$\left[x_i - \bar{x}\right]$	$\left[x_i - \bar{x}\right]^2$
	Method A				Method B		
1	144.83	7.40	54.76	1	143.02	6.19	38.32
2	141.46	4.03	16.24	2	141.02	4.19	17.56
3	139.02	1.59	2.53	3	136.09	.74	.55
4	140.89	3.46	11.97	4	136.47	.36	1.30
5	131.53	5.90	34.81	5	131.16	5.67	32.15
6	132.35	5.08	25.81	6	135.09	1.74	3.03
7	137.28	.15	.23	7	137.60	.77	.59
8	132.10	5.33	28.41	8	134.16	2.67	7.13
Avg.	137.43		Sum.=174.76	Avg.	136.83		Sum.=100.63
	S.D.=4.98				S.D.=3.78		
	Method C				Method D		
1	142.71	.89	.79	1	143.33	3.19	10.18
2	143.33	1.51	2.28	2	137.90	2.24	5.02
3	137.96	3.86	14.90	3	142.83	2.69	7.24
4	142.02	.20	.04	4	138.21	1.93	3.72
5	141.52	.30	.09	5	137.43	2.80	7.84
6	143.14	1.32	1.74	6	139.71	.43	.18
7	143.39	1.57	2.46	7	141.14	1.00	1.00
8	140.46	1.36	1.85	8	140.64	.50	.03
Avg.	141.82		Sum.= 24.15	Avg.	140.14		Sum.= 35.21
	S.D.=1.86				S.D.=2.24		

Table 9A, Cont.

Slice	Density	$[x_i - \bar{x}]$	$[x_i - \bar{x}]^2$
	Method E		
1	135.96	3.50	12.25
2	136.03	3.43	11.76
3	133.91	5.55	30.80
4	144.95	5.49	30.14
5	139.46	0	0
6	146.76	7.30	53.29
7	139.15	.31	.10
8	Specimen wasn't high enough for eight slices.		
Avg.	139.46	Sum.=138.34	

S.D.=4.81

Appendix D. Table 104. Dynamic Modulus Data

Sample	Temp	Load	Freq	Stroke						/E*/	∅
				MC	R	d	#Div.	Tot.d	in/in		
601I	70°F	100psi	6cyc/sec	20	.25	5.0 x10^{-4}	2.7	1.35 x10^{-3}	.169 x10^{-3}	5.917x10^{5}	17.3°
601J	70°F	100psi	6cyc/sec	20	.25	5.0 x10^{-4}	2.7	1.35 x10^{-3}	.169 x10^{-3}	5.917x10^{5}	17.3°
602I	70°F	100psi	6cyc/sec	20	.25	5.0 x10^{-4}	2.9	1.45 x10^{-3}	.181 x10^{-3}	5.524x10^{5}	21.6°
602J	70°F	100psi	6cyc/sec	20	.25	5.0 x10^{-4}	2.85	1.43 x10^{-3}	.178 x10^{-3}	5.617x10^{5}	21.6°
603I	70°F	100psi	6cyc/sec	20	.25	5.0 x10^{-4}	3.0	1.5 x10^{-3}	.188 x10^{-3}	5.319x10^{5}	25.9°
603J	70°F	100psi	6cyc/sec	20	.25	5.0 x10^{-4}	3.0	1.5 x10^{-3}	.188 x10^{-3}	5.319x10^{5}	27.0°
601C	70°F	50psi	6cyc/sec	10	.25	2.5 x10^{-4}	2.8	.70 x10^{-3}	.0875 x10^{-3}	5.714x10^{5}	16.5°
601D	70°F	50psi	6cyc/sec	10	.25	2.5 x10^{-4}	2.6	.65 x10^{-3}	.0812 x10^{-3}	6.157x10^{5}	16.2°
602G	70°F	50psi	6cyc/sec	10	.25	2.5 x10^{-4}	2.7	.675 x10^{-3}	.0844 x10^{-3}	5.924x10^{5}	21.6°
602D	70°F	50psi	6cyc/sec	10	.25	2.5 x10^{-4}	2.9	.725 x10^{-3}	.0906 x10^{-3}	5.518x10^{5}	21.6°
603C	70°F	50psi	6cyc/sec	10	.25	2.5 x10^{-4}	2.95	.737 x10^{-3}	.0922 x10^{-3}	5.542x10^{5}	26.4°
603D	70°F	50psi	6cyc/sec	10	.25	2.5 x10^{-4}	2.9	.725 x10^{-3}	.0906 x10^{-3}	5.518x10^{5}	26.8°

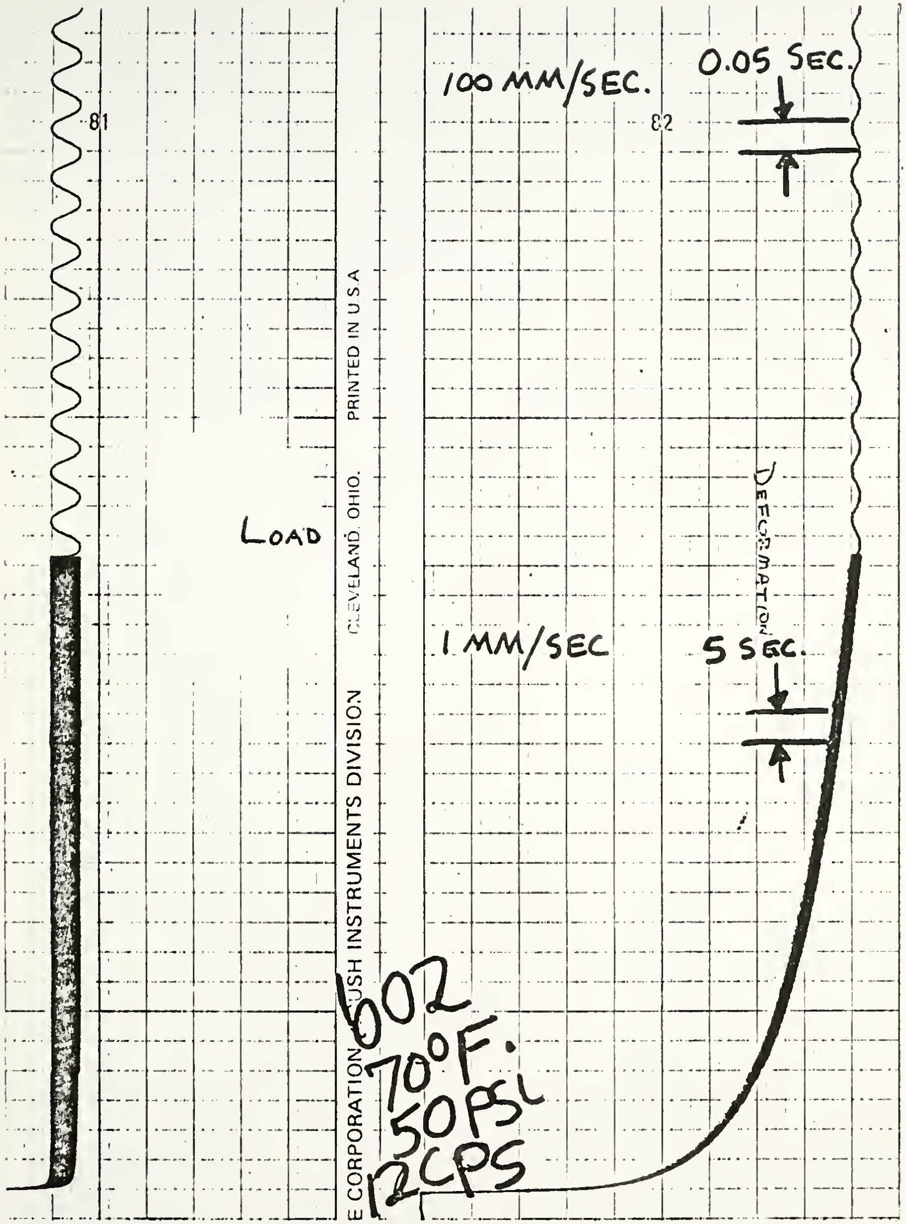

FIGURE 9. TYPICAL DYNAMIC MODULUS TEST TRACE.