JOINT HIGHWAY RESEARCH PROJECT

JHRP-74-18

A RECOMMENDED PROCEDURE FOR THE DETERMINATION OF THE DYNAMIC MODULUS OF ASPHALT MIXTURES

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Technical Paper

A RECOMMENDED PROCEDURE FOR THE DETERMINATION OF THE DYNAMIC MODULUS OF ASPHALT MIXTURES

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

December 17, 1974

Project: C-36-6AA

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

File: 2-4-27

Attached is a Technical Paper titled "A Recommended Procedure for the Determination of the Dynamic Modulus of Asphalt Mixtures", by Larry L. Yeager and Leonard E. Wood. This paper is a summary of the Final Report on the JHRP research project titled "Dynamic Modulus of Bituminoux Mixtures as Related to Asphalt Type" and presented to the Board in December 1973.

The authors have prepared the paper for presentation at the January, 1975 annual meeting of the Transportation Research Board in Washington, D. C. The paper is also planned for publication by the TRB.

The paper is presented to the Board as information and for approval of publication.

Respectfully submitted,

Harold L. Michael

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Technical Paper

A RECOMMENDED PROCEDURE FOR THE DETERMINATION OF THE DYNAMIC MODULUS OF ASPHALT MIXTURES

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Project No.: C-36-6AA

File No.: 8-5-19

Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana State Highway Commission

Prepared for Presentation at the January, 1975 Annual Meeting of the Transportation Research Board, Washington, D. C.

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December 17, 1974

ABSTRACT

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, gradation, and asphalt contents.

A RECOMMENDED PROCEDURE FOR THE DETERMINATION OF THE DYNAMIC MODULUS OF ASPHALT MIXTURES

Larry L. Yeager and Leonard E. Wood[1]

INTRODUCTION

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 $\sigma = \sigma_o \sin(wt)$, the resulting strain response is of the form $\varepsilon = \varepsilon_o \sin(wt-\phi)$ which lags the stress by the phase angle, ϕ. The complex modulus E^* is defined by;

$$E^* = E'+jE'' \quad (1)$$

where E^* = complex modulus

$E' = \frac{\sigma_o}{\varepsilon_o} \cos \phi$

$E'' = \frac{\sigma_o}{\varepsilon_o} \sin \phi$

j = imaginary number

σ_o = maximum stress applied - psi

ε_o = maximum strain experienced during test - in/in

ϕ = 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, ϕ, is a measure of the viscous response.

[1] Respectively, Aggregates Engineer, Martin Marietta Cement and Associate Professor, School of Civil Engineering, Purdue University, W. Lafayette, IN.

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

$$|E^*| = \frac{\sigma_o}{\varepsilon_o} \quad (2)$$

where

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

σ_o = maximum stress applied - psi

ε_o = maximum recoverable 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.

Current literature (1) provides ample background in the area of isolating those factors that influence the dynamic modulus, however, the concept of correlating a physical property of the asphalt cement to the dynamic modulus is still not prevalent in the literature.

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 ensue 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 between an asphalt property and the dynamic modulus of the mixture.

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 (2, 3).

Geologic setting for this material is the Liston Creek Limestone member (Huntington Litheface) of the Wabash formation of the Silurian period (4). 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 (5, 6).

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 (7) 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. The gradation chosen for this study meets the requirements of an Indiana State Highway surface mixture #9A (8) and a type IVb (9) mixture of the Asphalt Institute and is presented below.

Table 1. Sieve Analysis

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

Table 2. Aggregate Specific Gravities

Size	G_{bulk}	G_{bssd}	G_{app}	% Abs.
CA	2.52	2.59	2.71	2.79
FA	2.50	2.56	2.67	2.54
Filler	-	-	2.73	-

Asphalt

Three penetration grades of asphalt were used in this study;

hard asphalt - 60/70

normal asphalt - 85/100

soft asphalt - 120/130

A set of standard acceptance tests were run on each of the asphalts to characterize them. Results of these tests appear in Table 3.

The asphalt was produced by the American Oil Co. at their Whiting, Indiana refinery.

Table 3. Results of Asphalt Cement Characterization Tests

Asphalt Designation	101	102	103
Specification Tests			
Penetration 25°C, 100 gm. 5 sec.	56	85	122
Ductility 25°C, 5cm/min	100+	100+	100+
Sp. Gravity @ 25°C	1.028	1.027	1.022
Thin Film Oven Test 163°C, 5 Hrs. Penetration on Residue 25°C, 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 60°C Poise	2213	1236	678
Kinematic 135°C Cst	368	305	229
Softening Point R & B °F	129.2	121.3	113.3
Penetration Index	+.03	+.06	-.008

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

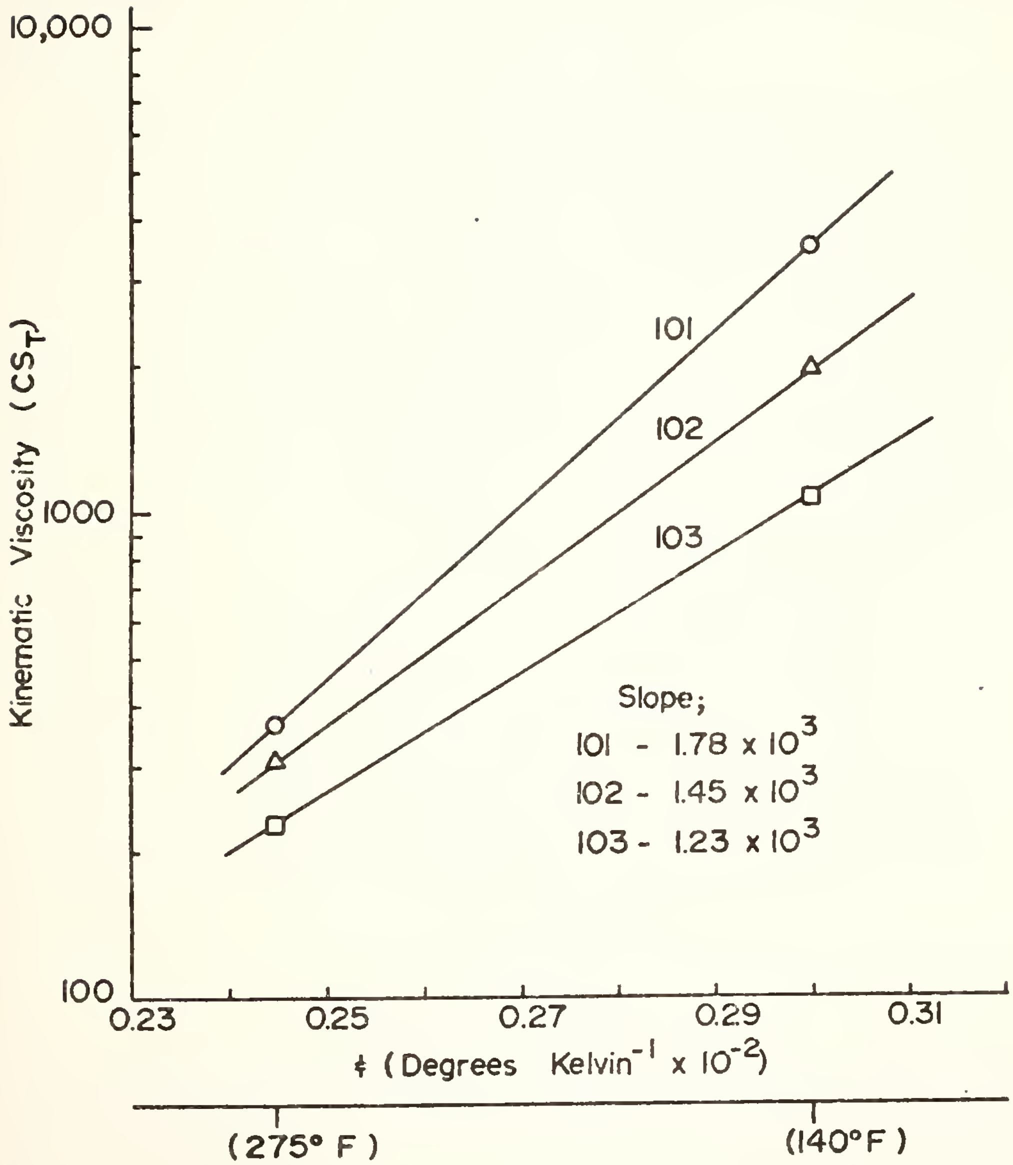

FIGURE I. RELATIONSHIP BETWEEN KINEMATIC VISCOSITY AND TEMPERATURE.

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 (10), were used to finalize the asphalt contents for the various bituminous paving mixtures included in this study. 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 then added and rodded in the prescribed manner. A leveling type kneeding compaction at 250 psi (1.7 MPa) foot pressure is applied for thirty tamps at which time the foot pressure is increased to 500 psi (3.4 MPa) 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 then compacted four to ten tamps with a foot pressure of 250 psi (1.7MPa). Once the top layer was compacted at 250 psi (1.7MPa) the higher compactive effort (500 psi) (3.4MPa) 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 (1.7 MPa) 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 (3.4 MPa) 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 (3.4 MPa) 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 0.05" per minute (1.27 mm/min), reaching an ultimate load of 1000 psi (6.9 MPa).

In all, five methods tried, the mixture was heated to 230°F (110°C) before being compacted. A 1000 psi (6.9 MPa) double plunger static load was applied at the rate of .05"/min (1.27 mm/min), after the kneeding compaction was completed and the specimen cooled in a 140°F (60°C) 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;

$$S.D. = \left[\frac{1}{N-1} \quad (X_i - \bar{X})^2 \right]^{1/2} \qquad (3)$$

Where:

S.D. = standard deviation

N = number of slices

X_i = density of each slice

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

The percent variation was calculated from the equation;

$$\% \text{ Var.} = \frac{(\bar{X}-X_i)}{\bar{X}} \times 100 \qquad (4)$$

Where

% Var. = per cent variation

X_i = density of each slice

$\bar{X}$ = 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 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.

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 gages were cemented vertically to the specimen at the mid-point of the 8 in. (20.3cm) 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 gage set-up was recorded by a Sanborn type 321 dual channel recorder. Duplicate strain gage set-ups were prepared on opposite sides (180^{o} apart) of each of the specimens and the output from each set of gages was recorded simultaneously. An average value was determined from the duplicate gage 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 (4.4°C) specimens) and a forced-air oven (for 70°F, (21.1°C) and 100°F (38°C) 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 (21.1°C).

In order to determine the temperature change one might experience in testing the specimens at temperatures other than 70°F (21.1°C), a study of temperature change versus time was made. An 1/8 inch (0.05 cm) hole was drilled to the center of a 4 inch (10.15cm) by 8 inch (20.3 cm) high specimen at the mid-point height. A temperature probe was placed in the hole and the specimen was brought to the test temperature (40°F 4.4°C) or 100°F) (3.8°C). 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.

There were two stress levels (50 (0.34MPa) and 100 psi.) (0.68MPa), three loading frequencies (1, 6 & 12 cyc/sec.), three temperatures at which tests were run 40°F, 4.4°C) 70°F (21.1°C), and 100°F, (37.8°C), and three asphalt cements (56, 85 and 122 pen). The aggregate gradation was the same for all tests.

In addition to the tests indicated previously, two additional tests were made for a comparison basis. Soaking three specimens for four days at 122°F (50°C) allowed a test to be conducted that would indicate qualitatively the effect that soaking has on the dynamic modulus value.

A set of specimens instrumented with strain gages was tested in order that a comparison could be made between that type of strain measurement and use of the LVDT present in the machine's loading system. Consistent data was obtained for each type of strain measurement indicating that either method is equally adequate for measuring strain at the stress level used in this investigation. 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 5 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 and Riley (11).

The phase lag angle is not used in the dynamic modulus calculation, but is useful when calculating the complex modulus. The phase lag angles (Ø) were calculated from the tests run on the specimens purely for the basis of quantitative comparison. These Ø values appear in Table 5 with the dynamic modulus measurements.

Table 5. Dynamic Modulus and Ø Values

			$/E^*/$, 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 (0.34MPa)	40	2.000	5.714	11.441	10.8	7.2	3.4
		70	1.333 1.310	5.465 5.405	8.880	13.5	10.4	6.8
		100	0.409	3.333	8.000	19.8	15.3	10.4
602	50 (0.34MPa)	40	3.300	8.649	10.684	18.0	8.6	5.6
		70	2.465 2.425	5.924 5.518	8.880	23.4	13.8	9.3
		100	0.297	3.330	7.280	28.8	19.3	13.8
603	50 (0.34MPa)	40	3.400	8.000	9.158	19.4	12.4	7.2
		70	3.205 2.650	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 (0.68MPa)	40	3.204	6.802 5.524	10.666	16.4	14.3	12.6
		70	2.265	5.917 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 (0.68MPa)	40	4.105	6.666 6.535	10.666	19.4	15.5	13.4
		70	2.680	5.617 5.524	8.880	26.3	20.8	17.8
		100	0.903	4.306	7.958	28.1	25.3	24.0
603	100 (0.68MPa)	40	4.567	6.666 6.410	10.666	23.9	20.1	15.7
		70	2.320	5.319 5.319	8.880	29.8	28.4	21.6
		100	1.004	4.459	8.000	36.5	34.3	33.0

Table 6 lists the data taken in two special test conditions. The first set of data was calculated from results of tests using SR-4 strain gages instead of the LVDT to measure specimen deformations. In the strain gage 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, (50°C). The other variables (temperature of test, cyclic rate, etc.) remained the same. For comparison purposes, the reader is directed to examine Tables 5 and 6 for the similar circumstances concerning the test conditions.

Table 6. Dynamic Moduli of Special Tests

Group	Load (psi)	Temp (°F)	Frequency (cps)	$/E^*/$, psi x 10^5 SR-4	LVDT
601*	50	70	1	1.645	1.32
602*	50	70	1	2.083	2.45
603*	50	70	1	3.333	2.93
				Soaked	Dry
601**	50	70	1	.400	1.32
602**	50	70	1	.400	2.45
603**	50	70	1	.349	2.93

* Strain Gage Measurement

** Soaked Specimens (4 days @ 122°F(50°C) LVDT measurement

Test data appears in Figures 2-7 and shows the relationship of the $\text{Log}_{10}\text{Log}_{10}$ (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.

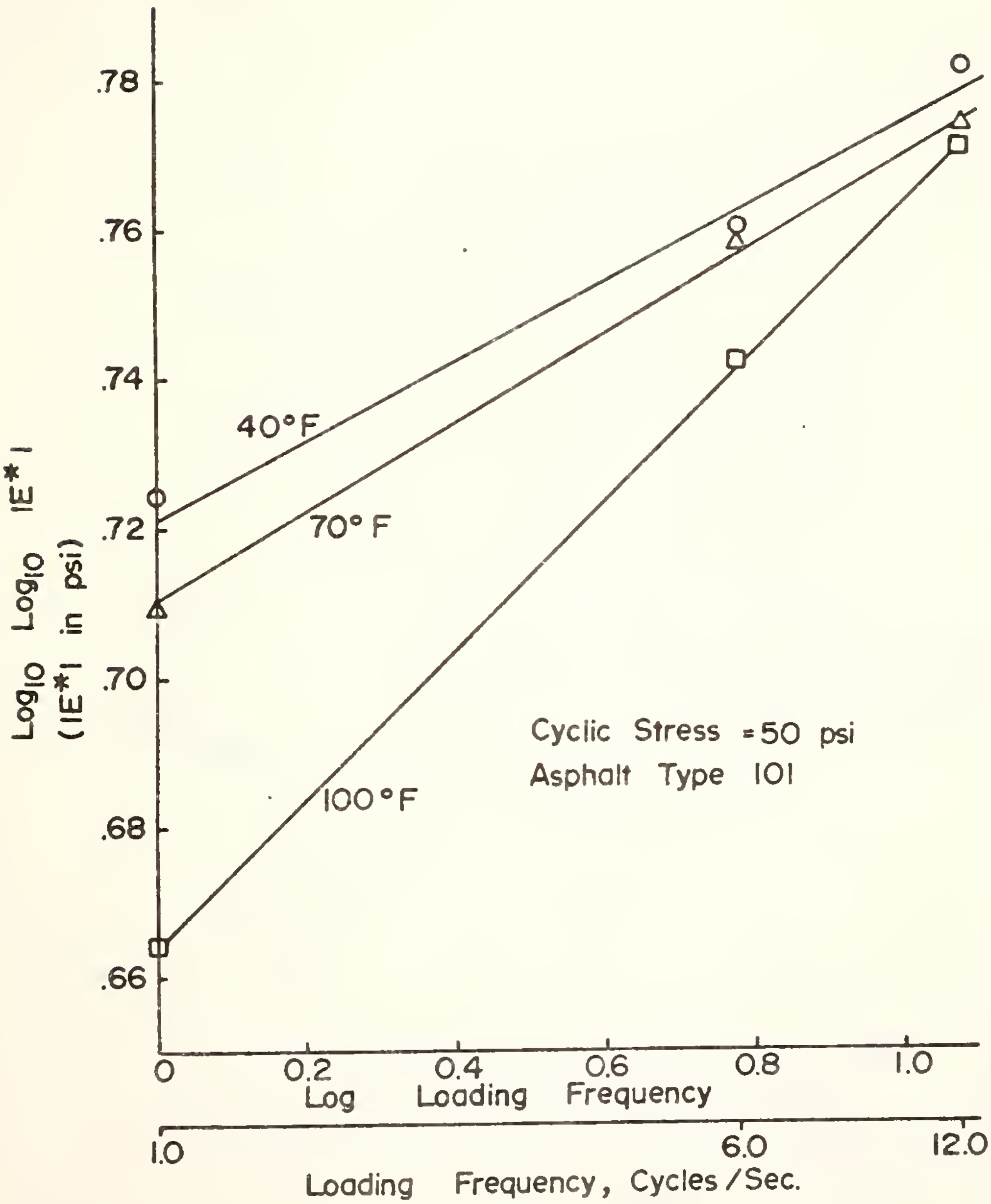

FIGURE 2. RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

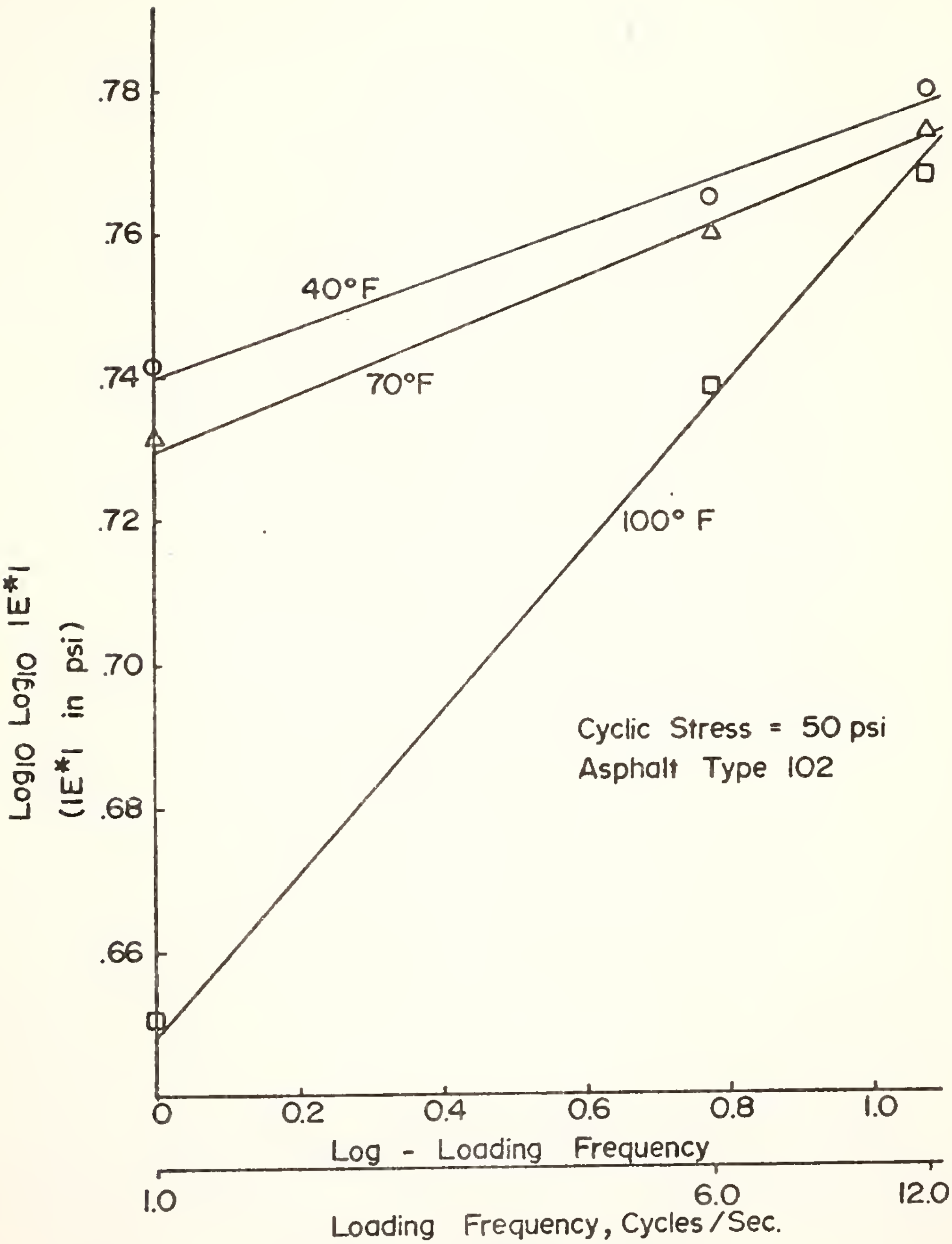

FIGURE 3 RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

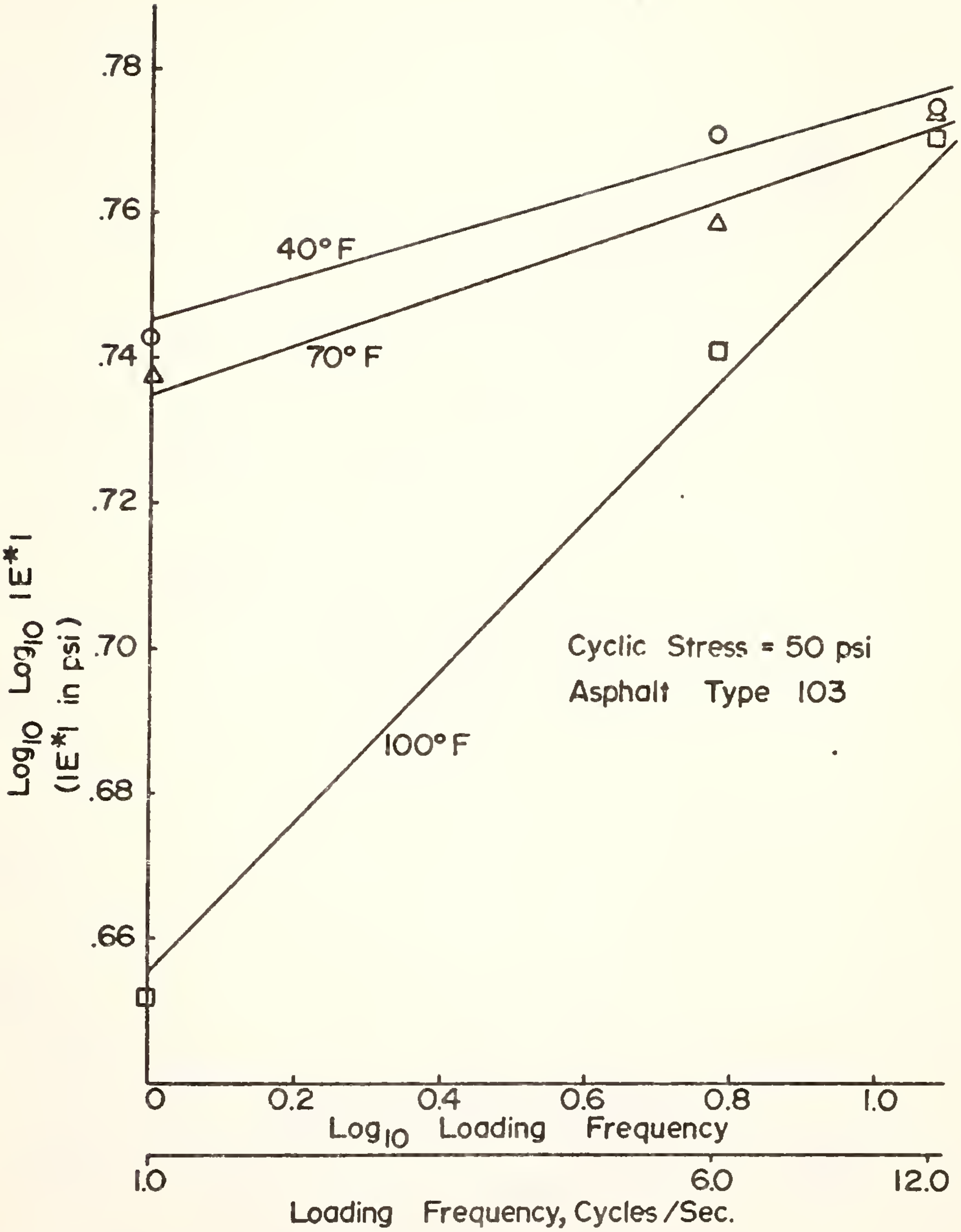

FIGURE 4 RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

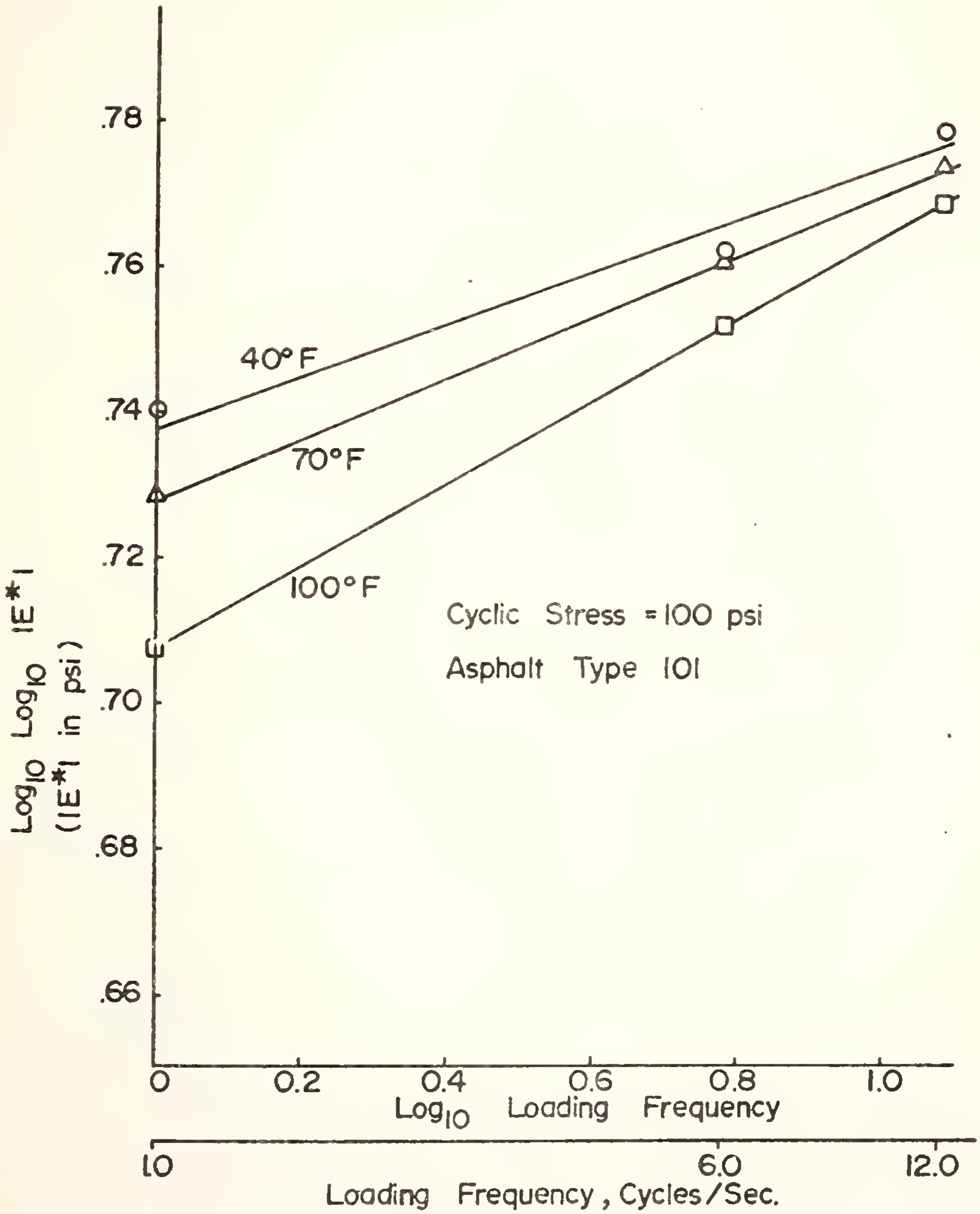

FIGURE 5 RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

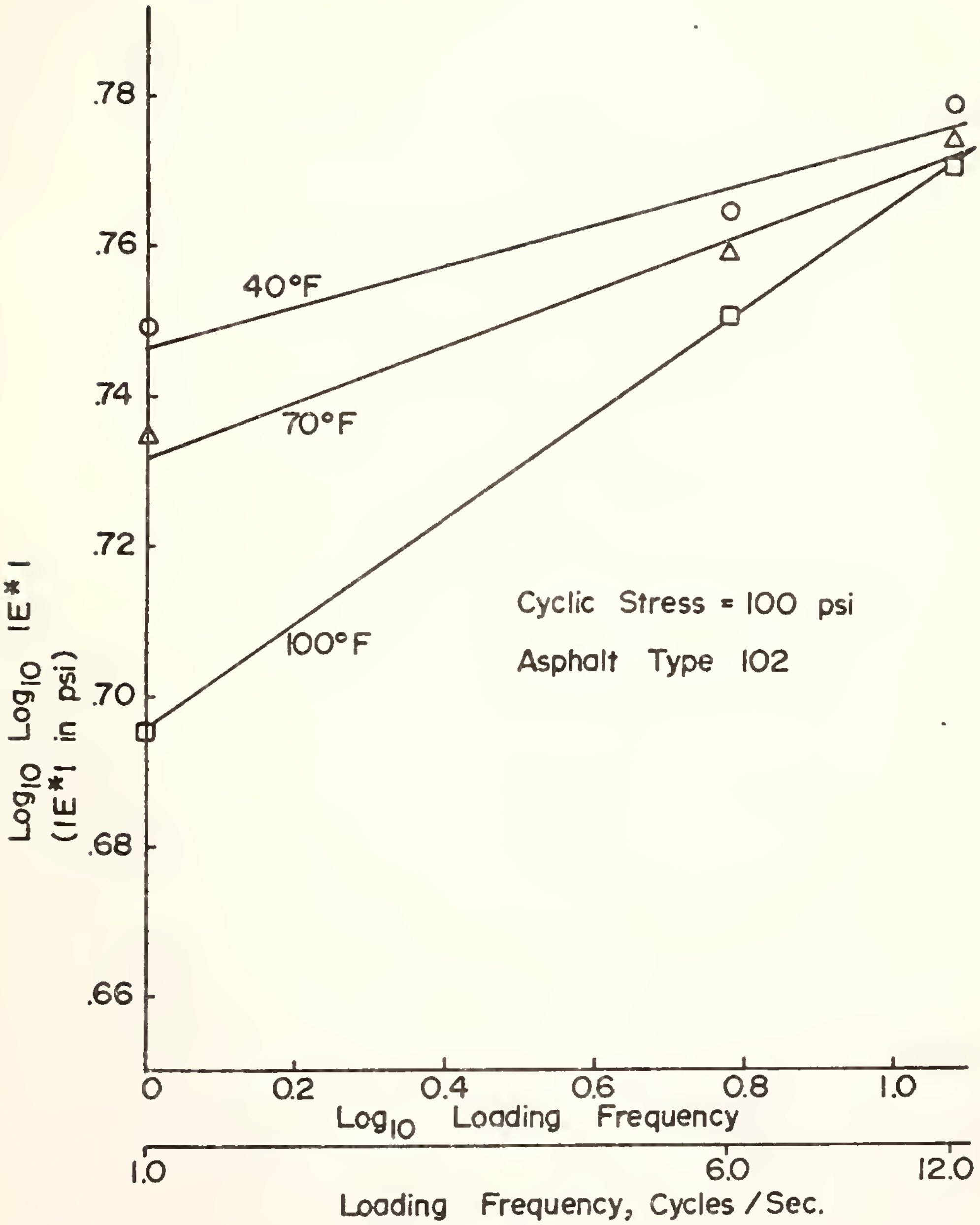

FIGURE 6 RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

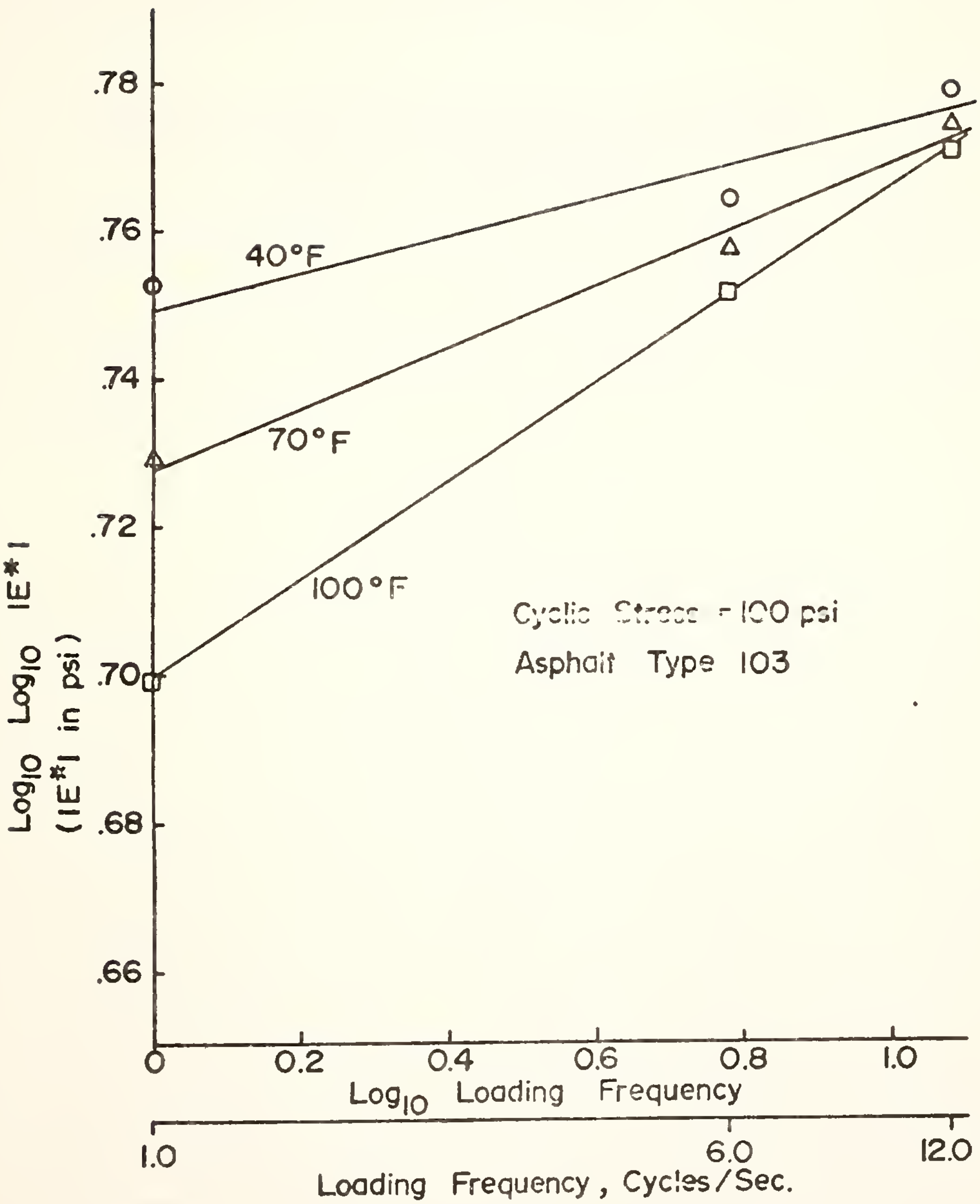

FIGURE 7. RELATIONSHIP BETWEEN LOG_{10} LOG_{10} DYNAMIC MODULUS AND LOG_{10} FREQUENCY.

The three lines represent the relationship between $Log_{10}Log_{10}$ (dynamic modulus) and Log_{10} (frequency) at one, six and twelve cps for temperatures of 40^o, 70^o, and 100^oF (4.4, 21.1, and 3.78^oC).

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 (0.34MPa) and loading rate of 1 cycle/sec. (See Fig. 2) the modulus decreases from 2.00×10^5 psi at $40^oF(4.4^oC)$ to 0.409×10^5 psi at 100^oF (37.8^oC). 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 (0.34MPa) the value of the dynamic modulus varied from 11.41×10^5 psi for $40^oF(4.4^oC)$ to 8.00×10^5 psi for $100^oF(37.8^oC)$.

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 (12). 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 (0.34MPa), a temperature of 40°F (4.4°C), 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 (13) 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:

$$V = f\gamma \qquad (5)$$

where;

V = velocity (ft/sec)

f = frequency (sec^{-1})

γ = 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 (0.34 and 0.68MPa) 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

(0.46 MPa) for temperatures of 40, 70, and 100°F(4.4, 21.1, and 3.78°C). 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 (0.34 and 0.68MPa) with exception occurring when one uses a cyclic stress of 100 psi (0.68MPa) at the extreme conditions of temperature (100°F(37.8°C) 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. However, the significance of asphalt type was minimal when one considers the Dynamic Modulus values obtained in this study.

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°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:

$$\log /E^*/ \quad = \quad \log (x_1)(x_2) + x_3 \qquad (6)$$

where

$/E^*/$ = Dynamic Modulus

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

x_2 = $\log T - \left[\frac{\log T - \log 40}{0.710}\right]$

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

T = temperature at which test will be made in ^oF.

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 7. Logarithms of the Dynamic Moduli of the Experimental and Calculated Values

			Log_{10} $/E^*/x10^5$ psi Experimental	Log_{10} $/E^*/x10^5$ psi Calculated
Sample 601	40F (4.4^oC)	1	5.301	5.206
		6	5.757	5.945
		12	6.058	6.285
50 psi (0.34MPa)	70F (21.1^oC)	1	5.120	4.884
		6	5.735	5.662
		12	5.948	5.963
	100F (37.8^oC)	1	4.612	4.680
		6	5.522	5.458
		12	5.903	5.759

Table 7 lists the various logarithmic values of the dynamic moduli from the experimental tests as well as those values calculated from equation 6. The comparison in Table 7 is for asphalt type 101, tested at a stress level of 50 psi (0.34MPa) and for temperatures of 40^{o}, 70^{o}, and $100^{o}F$ (4.4^{o}, 21.1^{o}, and $37.8^{o}C$) and 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 $100^{o}F(37.8^{o}C)$.

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 $122^{0}F(50^{o}C)$. The dynamic modulus values for the unsoaked condition at $70^{o}F(21.1^{o}C)$ 50 psi (0.34MPa) and 1 cycle per second (taken from Table 5) 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 a $.349 \times 10^{5}$ psi for group 603 (values are from Table 6). As may be noted from Table 6 the three values listed for the soaked specimens are considerably less than

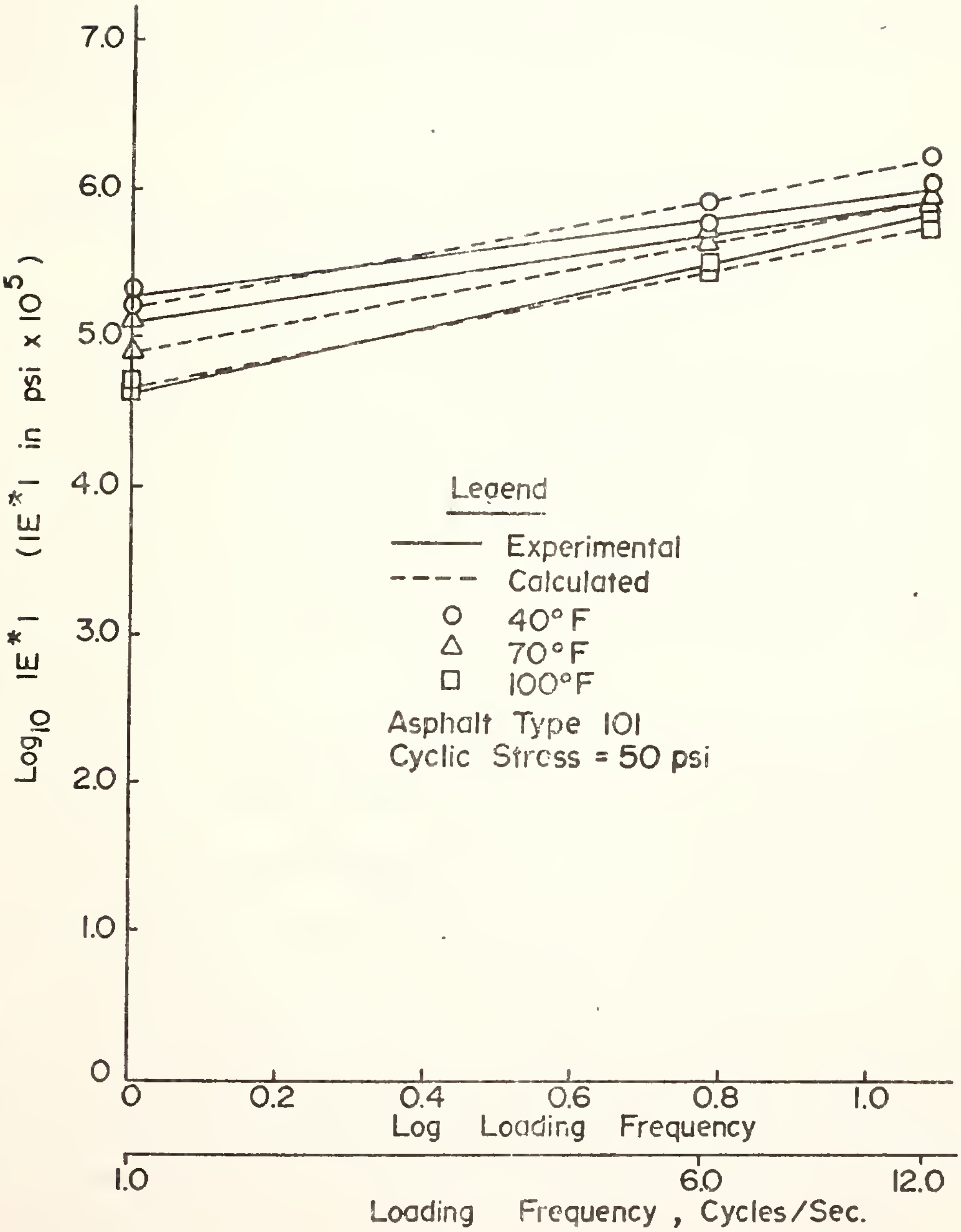

FIGURE 8. RELATIONSHIP BETWEEN CALCULATED VALUES OF DYNAMIC MODULUS PLOTTED WITH EXPERIMENTAL VALUES AND CYCLIC LOADING RATE.

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-hydraulic testing machine with a Brush 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 continuously to the mold. The tamping foot is allowed to compact the mixture at 250 psi (1.7MPa) 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 (3.4MPa) 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 $140^{o}F(60^{o}C)$ oven for one and one-half hours at which time a 1000 psi (6.8MPa) double plunger static load is applied at the rate of .05"/min (1.3 mm/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 (0.34MPa) 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 (.8, 4, 80 Km/hr), respectively, and closely resembles speeds experienced on many bituminous pavements. (See page 30, equation 5). Three temperatures of $40^{o}F$, $70^{o}F$, and $100^{o}F$ ($4.4^{o}C$, $21.1^{o}C$, and $37.8^{o}C$) 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

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) 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),

$$\text{Log } /E^{*}/ = \text{Log } (x_1)(x_2) + x_3 \qquad (6)$$

b) Soaking a four by eight inch high specimen for four days in a $122^{o}F(50^{o}C)$ water bath reduces markedly the dynamic modulus value for the particular aggregate type used in this study and minimized the role of the asphalt.

c) A stress level of 100 psi (0.68MPa) at the extreme conditions of temperature ($100^{o}F$) ($37.8^{o}C$) and cyclic rate (1 cycle per second) resulted in non-linear values of dynamic modulus.

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