Some Aspects of the Rheological Behavior of Bituminous Mixes

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Rheological behavior of bituminous mixtures was studied and evaluated in terms of the theory of linear viscoelasticity. The material studied was tested under static loading conditions and its behavior under dynamic load was predicted by using the linear viscoelasticity theory.

Literature was reviewed and summarized. Tests were conducted under flexural and tensile stress conditions at three temperatures: 40, 70, and 100 F. Results were evaluated in terms of the complex modulus of elasticity, determined from curvature measurements of flexure specimens under creep-strain loading.

General trends for the complex modulus were established for bituminous mixes under the influence of temperature, applied load, curing time after compaction, and binder content of the mix.

In predicting the dynamic behavior of these materials from static tests by means of the complex modulus, it was found that such a prediction was significantly affected by the magnitude of the initial strain value in the creep-strain curve. The total response of the material was found to be mainly viscous in nature. As expected, temperature had a significant effect on the strength of the material and also affected critically the relationship between curvature and applied load.

•BASED on scientific tradition established over the past century and a half it is usually assumed that solids are elastic and obey certain laws, while liquids are viscous and obey a different set of rules. The difficulty with this approach is that each time a material deviates from the idealized properties of either extreme a new set of rules has to be established (13). The problem is compounded by the fact that, while some materials may be characterized through their mechanical properties in a relatively simple manner, characterization of most materials used in modern technology represents a challenge. This is because most materials fit neither of the two idealized classes of materials mentioned. The increasing use of polymers, or combined materials such as the soil-asphalt mixtures with which this study is concerned, makes it increasingly important to explore the response of these materials to applied stresses in light of their true behavior.

A material that has a partially elastic and partially viscous response is referred to as a viscoelastic material. Many viscoelastic materials exhibit nonlinear viscoelastic properties. Nevertheless, their behavior can be explained to a useful degree of approximation by the theory of linear viscoelasticity (12). This investigation concerned the evaluation of rheological behavior of bituminous mixtures under static creep-strain conditions. The complex modulus of elasticity was used with two objectives in mind: (a) as a means to evaluate the experimental findings developed in this study, and (b) as

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a tool in evaluating the probable response of bituminous mixtures under dynamic load conditions. In the latter, the complex modulus of elasticity was used in transferring results from static creep-strain tests from the time domain to the frequency domain.

The main objectives of the study were:

1. To study the behavior of bituminous mixtures and evaluate that behavior in terms of the complex modulus concept of the theory of linear viscoelasticity;
2. To determine the influence of selected factors such as temperature, curing time after compaction, applied load, and binder content on the rheological behavior of such mixtures; and
3. To establish trends in the behavior of bituminous mixtures as affected by the factors studied in the course of this investigation.

Because of the extreme variability of the materials involved, the scope of this study is necessarily limited. The applicability of the results is limited to the materials used in this study, and consequently these results cannot be applied indiscriminately. However, the general trends established can be extended to similar materials.

SOIL-ASPHALT MIXTURES AS VISCOELASTIC MATERIALS

The ability of the linear viscoelastic analysis to describe the behavior of bituminous mixtures has been a point of disagreement among investigators in the field. The temptation to use empirical results based on certain laboratory or field tests has been overwhelming in the past. The problem with this type of approach is that it encompasses in one or several parameters an extremely complex system of stresses, further complicated by the presence of several variables.

In view of these circumstances, several investigators have turned their attention toward a more fundamental approach in an attempt to reach an understanding of the true behavior of the materials under specific stress conditions, and to isolate the effect that the many variables might have on it. Such an approach has been used on flexible pavement systems in general, as well as on different types of asphaltic mixtures including soil-asphalt mixtures.

Although Skok and Finn (21) used an elastic analysis for asphaltic concrete pavement, they pointed out that the viscoelastic analysis should be the basic tool in examining the behavior of asphaltic mixtures once the mathematical difficulties of that approach had been streamlined. The theory of viscoelasticity is the logical tool for analyzing the materials that fall between the elastic and viscous extremes, and can also be a factor in simplifying the mathematical problems in analyzing pavements with viscoelastic materials. Baker (3), concurring that the rheological concepts developed through the theory of viscoelasticity permitted a more accurate representation of properties, advocated the use of those properties calculated by using the rheological concepts in an elastic theory of pavement analysis. Monismith and Secor (14) conclude that, at least for slow rates of loading, it appears that viscoelastic theory may be required to predict the behavior of asphalt concrete pavements. Wood and Goetz (24) found that sheet asphalt mixtures obeyed the laws of linear viscoelasticity for limited stresses and small deformations.

The majority of the investigators seem to agree that the viscoelastic approach toward explaining the behavior of soil-aggregate mixtures stabilized by means of a viscous binder is the most promising. Nevertheless, some investigators feel that an elastic analysis and predictions of behavior based solely on elastic theories, or modification thereof, offer a sufficiently good approximation.

FACTORS INFLUENCING BEHAVIOR OF SOIL-ASPHALT MIXES

The rheological properties of bitumen-mineral aggregate compositions are highly temperature-dependent. Many investigators have turned their attention lately to the significant task of evaluating these rheological properties. In one such study, Pagen (16) used the complex modulus concept presented by Papazian (17) to evaluate the rheological response of bituminous concrete under dynamic loading. The concept of the

complex modulus used in the course of this investigation will be covered in detail in the next section of this paper. Because of the apparent success of this approach, it was selected for use in this investigation to evaluate and predict the rheological behavior of bituminous mixtures under static and dynamic loading conditions.

Abdel-Hady and Herrin (1), in a study made on compacted soil-asphalt mixtures with a medium-curing liquid asphalt as a binder, provided additional proof of the susceptibility of these materials to the rate of loading being applied. In the same study the importance of curing time after compaction, as shown by its influence on the rheological properties of the material, was established.

Most of these studies were performed with the material in compression or under more complex stress conditions such as those occurring in flexible pavement slabs. Tons and Krokosky (23) studied certain properties of bituminous concrete in tension. From this study the effects of temperature and loading time on the mixes were determined for this state of stress.

Complex Modulus Concept

The complex modulus concept is based on the steady-state response of a linear viscoelastic material when subjected to sinusoidal stress (6). When such a material is placed under an alternating stress of a given frequency, its response will be a sinusoidal strain of the same frequency that lags the stress by a phase angle ϕ.

If the applied stress is separated into two components, one in phase with the strain and the other 90 deg out of phase, then the ratio of the amplitude of the in-phase component of the stress to the amplitude of the stress to the amplitude of the strain represents the real part of the complex modulus. The ratio of the amplitude of the 90 deg out-of-phase component of the stress to the amplitude of the strain represents the imaginary part of the complex modulus (10).

Since no mention has been made of the type of stresses applied, it should be understood that the idea of the complex modulus M^* is completely general. The real and imaginary parts, M' and M'', of the complex modulus M^* may be added vectorially on a complex plane to give $M^* = M' + iM''$. The absolute value of M^*, which is a member of the set R, is given as the ratio of the amplitude of the stress to the amplitude of the strain. Analogous definitions can also be given. For example, the complex modulus of elasticity E^*, the complex shear modulus G^*, and the complex bulk modulus K^* can appropriately be described by the stress and strain relationships. The work in this investigation will be concerned only with the complex modulus of elasticity E^*.

Investigators concerned with the viscoelastic behavior of materials have used a variety of methods to obtain the complex modulus. These methods vary from the elegant method of Philippoff (19, 20) for measuring deformation in shear, through the simple flexure device of Müller (15), to the experiments of Aleksandrov and Lazurkin (2), which provide only the absolute value of the complex modulus as the end result of their experiments. In this investigation the complex modulus of elasticity was obtained by a mathematical transformation based on a creep-strain test, following the method presented by Papazian (18).

The basic test used was a simple flexure test under static load. It was performed on a small beam specimen with static loading applied for a specific time interval. Results from tests were evaluated in terms of the rheological characteristics of the material, following the concepts derived from the complex modulus presented by Papazian (18).

Properties of Materials and Mix Design

The two basic soils in this investigation were designated as I-1 and K-1. The properties and gradation of these soils are given in Table 1. In both cases, an 85-100 penetration asphalt cement with a specific gravity of 0.9983 was used as the binder in the preparation of the mixtures.

In general, the Marshal method of mix design as described in ASTM D 1559-62 T was used to determine the optimum asphalt content. The only deviation from standard

procedures was that the specimens were tested at 70 F instead of the prescribed 140 F. This deviation is justified on the basis that, while 140 F is a reasonable estimate of what one might expect at the surface of a pavement, the base materials being considered in this investigation would never reach that temperature. This lower temperature is consistent with the recommendations of Kallas (11), who recommends that the testing temperature for Marshall specimens be lowered to 110 F or 100 F for asphaltic concrete mixes to be used in thicker pavement slabs. This suggests that the testing temperatures for a mix to be used strictly as a base or subbase material should be substantially lower.

TABLE 1

PROPERTIES OF SOILS INVESTIGATED

Designation	I-1	K-1
Particle size distribution (percent passing)		
¾ in.	100	100
No. 4	74	86.5
No. 10	54	75.5
No. 40	22	20.5
No. 200	25	2
Liquid limit	18.9	
Plasticity index	NP	NP

Testing Procedure

The test specimens were 3- by 3- by 12-in. beams. The material was mixed in a heavy-duty kitchen-type mixer capable of mixing approximately 50 lb at a time. The mixer was modified to suit the needs of this investigation by placing a smaller mixing bowl fitted with a steel collar into a larger bowl. A uniform space of approximately 2 in. remaining between the bowls was filled with oil, and a gas heater was used to heat the oil. Once the heating process started, the temperature of the oil rose in a uniform manner, thus creating a uniformly heated bath for the mixing bowl itself.

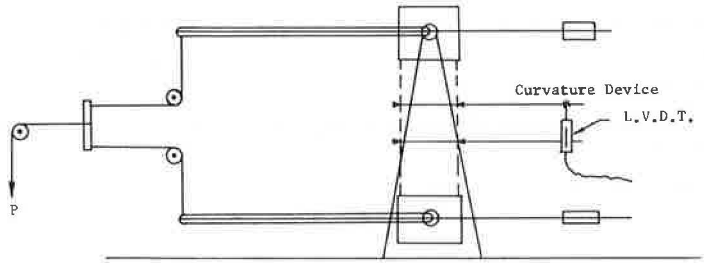
After thorough mixing of the heated constituents, the desired amount of mixture was weighed and placed in the mold. This amount was calculated from the design characteristics of the mix and the known volume of the mold so as to achieve a specified compacted density. The material in the mold was compacted under static pressure by applying compactive pressure at the top and the bottom of the mold. After compaction the mold was carefully disassembled and the compacted beam transferred onto a flat wooden board where it was allowed to cool at room temperature. Precautions were taken to avoid imposing any external stresses upon the beam specimen during cooling.

All tests performed in the course of this investigation were carried out at a specified constant temperature. This was achieved by using a constant-temperature room in which the temperature was accurately controlled within ± 0.5 F. Temperatures selected for this investigation were 40, 70, and 100 F. In order to have a uniform temperature throughout the specimen during the test, test specimens were placed in the constant-temperature room for a minimum of 24 hours before the actual testing time.

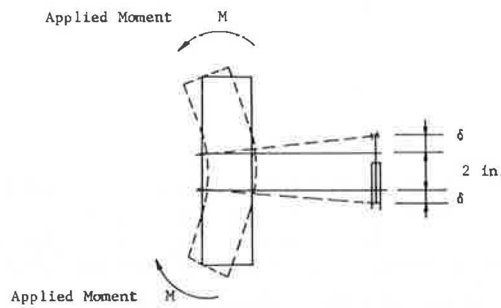
Since no standard procedure or apparatus existed for the type of test conducted, it was necessary to design a testing apparatus. This was done with the following objectives in mind: (a) the design should be mechanically simple; (b) it should be flexible enough to allow for future desirable modifications or adaptations for different load application systems (for example, dynamic loading); and (c) the testing apparatus should produce simple bending, eliminating as many complicating stress factors as possible. The flexural testing device (Fig. 1) consists essentially of a frame supporting two hinged end-boxes designed to apply equal moments to both ends of the test specimen. Equal end-moments were achieved by using a mechanical system of pulleys and levers.

The load (P) was applied manually, exercising great care to hold dynamic effects to a minimum. This method of loading, although presenting some problems, worked satisfactorily throughout the test program. Alternate methods of load application considered in the early stages of the investigation all resulted in considerable mechanical complication of the testing device, with a consequent economic penalty to the program. The consistently good results obtained by the manual method did not seem to justify more complicated designs needed for a different method of load applications.

The nature of both the data and the material being evaluated made it necessary to design special instrumentation to obtain the desired data. The apparatus designed for this purpose, called the curvature device, is also shown in Figure 1. This device



(a) Illustration of the Flexural Test



(b) Working Principle of the Curvature Device

Figure 1. Flexural testing device and the curvature device.

consisted essentially of two rigid aluminum frames fastened to the beam a fixed distance apart. A LVDT attached to the ends of the aluminum frame was calibrated to indicate the average curvature in the specimen between the aluminum frames. Output from the LVDT was recorded continuously on a strip recorder to give a continuous record of curvature with time under a constant moment.

Sample Size and Repeatability of Results

The total number of tests carried out during this program exceeded 900. For every condition, i.e., for a given mix, load condition, and temperature, from two to four samples were tested. In some isolated cases up to six samples were tested for one particular set of conditions. In general, good agreement was obtained between repeated tests under identical conditions. In those cases where the result from subsequent test specimens differed by more than 20 percent from those of the first specimens tested, the size of the sample was increased to insure representative results.

ANALYSIS AND PRESENTATION OF RESULTS

The concept of complex modulus of elasticity has been used widely by investigators in all branches of rheology (8) and has been an accepted standard for comparing results of rheological studies obtained by different techniques and on different materials (9). In this investigation a non-dynamic method of determining the complex modulus is used.

Papazian (17) showed that the complex modulus E^* can be obtained as a function of frequency from static creep tests and an appropriate Fourier transform. The advantages of this approach are easily recognized; it eliminates the inherent complication of a dynamic test and, at the same time, provides the means of obtaining the desired results. Once E^* is expressed in terms of frequency, it is merely a matter of algebraic operations to obtain the absolute value of E^*, $|E^*|$, for any chosen frequency (7). This eliminates the need for testing many specimens at different frequencies.

The complex modulus of elasticity may be calculated by obtaining the response of the material to an applied stress that is constant in time, applying a Fourier transform to both stress and strain in order to express them in terms of frequency, and then taking the ratio of the transformed stress and strain functions. To achieve better accuracy, the Fourier transform of the differentiated function $\dot{\epsilon}(t)$ was used in these calculations rather than the transform of the original function $\epsilon(t)$. The function $\dot{\epsilon}(t)$ was differentiated graphically, yielding equations of the form $A_i e^{-k_i t}$ for a series of straight-line approximations of the $\epsilon(t)$ curves.

Once this process of graphical differentiation was completed, an approximation for $\dot{\epsilon}(t)$ was obtained by adding all the exponential expressions representing the straight-line approximations of the $\epsilon(t)$ curve to the constant or steady-state rate of strain $\dot{\epsilon}_{ss}$. From these expressions the rate of strain ($\dot{\epsilon}$) is expressed as function of time by

$$\dot{\epsilon}(t) = A_1 e^{-k_1 t} + A_2 e^{-k_2 t} + \ldots + A_n e^{-k_n t} + \dot{\epsilon}_{ss} \tag{1}$$

To obtain the rate of strain in terms of frequency, a Fourier transform was applied to yield

$$\dot{\epsilon}(i) = \frac{A_1}{k_1 + i\omega} + \frac{A_2}{k_2 + i\omega} + \ldots + \frac{A_n}{k_n + i\omega} + \frac{\dot{\epsilon}_{ss}}{i\omega} \tag{2}$$

The transform of the strain was obtained through the relation

$$\epsilon^*(i\omega) = \frac{1}{i\omega}\left[\dot{\epsilon}^*(i\omega) + \epsilon(0)\right] \tag{3}$$

where $\epsilon(0)$ is the initial strain at $t = 0$.

Results from the testing program, however, showed little or no initial strain. Hence the $\epsilon(0)$ term approached zero. This is clearly illustrated by the typical strain-time curve shown in Figure 2. Absence of an initial strain $\epsilon(0)$ was consistent throughout this study; hence, it must be concluded that for these materials strain is a continuous

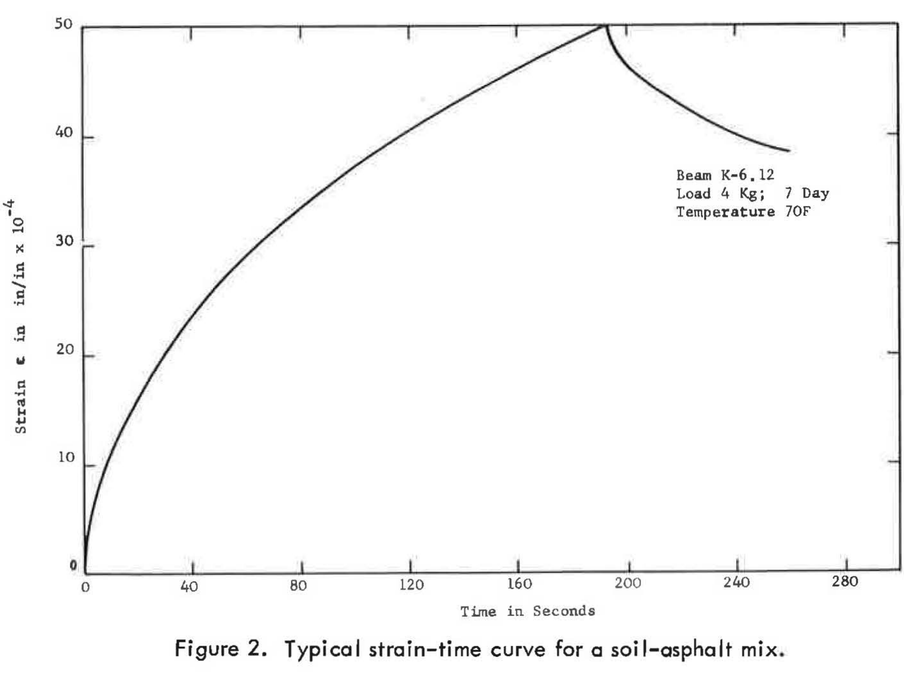


Figure 2. Typical strain-time curve for a soil-asphalt mix.

function of time, with no discontinuities at the origin and with a single point of contact at the origin. Equation 3 then becomes

$$\epsilon^* (i\omega) = \frac{1}{i\omega} \left[\dot{\epsilon}^* (i\omega) \right] \tag{4}$$

Substituting the transform of the strain rate by its equivalent expression in Eq. 4, the strain transform is given as a function of frequency by

$$\epsilon^* (i\omega) = \frac{1}{i\omega} \left[\frac{A_1}{k_1 + i\omega} + \frac{A_2}{k_2 + i\omega} + \ldots + \frac{A_n}{k_n + i\omega} + \frac{\dot{\epsilon}_{ss}}{i\omega} \right] \tag{5}$$

The Fourier transform of $\sigma(t)$ is given (22) by

$$\sigma^* (i\omega) = \int_{-\infty}^{\infty} \sigma(t) e^{-i\omega t}\, dt \tag{6}$$

The applied stress, as used in this investigation both in flexure and in tension, is equal to

$$\begin{aligned} \sigma(t) &= \sigma_0 \quad \text{for } t > 0 \\ \sigma(t) &= 0 \quad \text{for } t < 0 \end{aligned}$$

where σ_0 is the applied stress due to static load.

Substituting these values in Eq. 6, it is found that the transform of $\sigma(t)$ is equal to

$$\sigma^* (i\omega) = \int_{0}^{\infty} \sigma_0 e^{i\omega t}\, dt \tag{7}$$

Integrating the expression in Eq. 7, the value of $\sigma^* (i\omega)$ becomes

$$\sigma^* (i\omega) = \frac{\sigma_0}{i\omega} \tag{8}$$

Using the basic relationship for the modulus of elasticity, the complex modulus can be expressed as

$$E^* (i\omega) = \frac{\sigma^* (i\omega)}{\epsilon^* (i\omega)}$$

Substituting the expressions for $\epsilon^* (i\omega)$ and $\sigma^* (i\omega)$ as given by Eqs. 5 and 8, the complex modulus E^* is obtained as a function of frequency in the form

$$E^* (i\omega) = \frac{\sigma_0}{\frac{A_1}{k_1 + i\omega} + \frac{A_2}{k_2 + i\omega} + \ldots + \frac{A_n}{k_n + i\omega} + \frac{\dot{\epsilon}_{ss}}{i\omega}} \tag{9}$$

Equation 9 was the basic expression used to calculate the complex modulus E^* from the data obtained in the laboratory testing program.

Complex Modulus as a Function of Frequency

The only difference between the expression shown in Eq. 9 and the analogous expression derived by Papazian (17, 18) is the additional initial strain value $\epsilon(0)$ that appears in the denominator of Papazian's work and as shown in Eq. 10:

$$E^*(j\omega) = \frac{\sigma_0}{\frac{A_1}{k_1 + j\omega} + \frac{A_2}{k_2 + j\omega} + \ldots + \frac{A_n}{k_n + j\omega} + \frac{\dot{\epsilon}_{ss}}{j\omega} + \epsilon(0)} \tag{10}$$

In order to express E* in terms of frequency on the real plane and to evaluate the influence that some of the variables have on this parameter, it is necessary to compute the absolute value of E*. Comparison of the absolute value of E* as determined from Eqs. 9 and 10 when plotted against frequency shows there is a fundamental difference in the two curves. Since the only difference between Eqs. 9 and 10 is the initial strain term $\epsilon(0)$ that appears only in Eq. 10, the difference must be due to this factor. To evaluate the influence of initial strain $\epsilon(0)$ on the final expression for $|E^*|$, consider the completely general expression for E*, which can be written as

$$E^* = \frac{K_0}{\sum_{k=1}^{n} \frac{A_k}{K_k + i\omega}} \tag{11}$$

Equation 11 corresponds to the expression for E* as indicated in Eq. 9. The values K_0, A_1, and A_k are constants. In order to obtain the absolute value of E*, certain algebraic operations must be performed:

$$E^* = \frac{K_0}{\frac{K_k - i\omega}{K_k - i\omega} \sum_{k=1}^{n} \frac{A_k}{K_k + i\omega}} \tag{12}$$

Multiplying and dividing the denominator by the conjugate of the denominators appearing within the sum and performing the operations indicated in Eq. 12, the expression for E* can be reduced to

$$E^* = \frac{K_0\, P_{2n}(\omega)}{Q_{2n-2}(\omega) - i\, Q_{2n-1}(\omega)} \tag{13}$$

where $P(\omega)$ and $Q(\omega)$ are polynomials in ω and the subscripts indicate the degree of the polynomials. Multiplying and dividing Eq. 13 by the conjugate of the denominator gives

$$E^* = \frac{K_0\, P_{2n}(\omega) \cdot \left[Q_{2n-2}(\omega) + i\, Q_{2n-1}(\omega)\right]}{\left[Q_{2n-2}(\omega) - i\, Q_{2n-1}(\omega)\right]\left[Q_{2n-2}(\omega) + i\, Q_{2n-1}(\omega)\right]} \tag{14}$$

Equation 14 can be reduced to

$$E^* = \frac{K_0\, P_{2n}(\omega)\left[Q_{2n-2}(\omega) + i\, Q_{2n-1}(\omega)\right]}{\left[Q_{2n-2}(\omega)\right]^2 + \left[Q_{2n-1}(\omega)\right]^2} \tag{15}$$

Separating the real and imaginary parts,

$$E^* = \frac{R_{4n-2}(\omega)}{M_{4n-2}(\omega)} + i\,\frac{N_{4n-1}(\omega)}{M_{4n-2}(\omega)} \tag{16}$$

where R, M, and N are again polynomials in ω. The absolute value of E* is then given by

$$|E^*| = \sqrt{\left[\frac{R_{4n-2}(\omega)}{M_{4n-2}(\omega)}\right]^2 + \left[\frac{N_{4n-1}(\omega)}{M_{4n-2}(\omega)}\right]^2} \tag{17}$$

Equation 17, however, can be reduced to the form

$$|E^*| = \frac{\sqrt{L_{8n-2}(\omega)}}{M_{4n-2}(\omega)} \tag{18}$$

which in turn can be expressed as

$$|E^*| = \frac{|\omega^{4n-1}|\,|C_0|}{|\omega^{4n-2}|} \cdot \frac{\sqrt{1 + \frac{c_1}{\omega} + \frac{c_2}{\omega^2} + \dots}}{\left|\left(1 + \frac{m_1}{\omega} + \frac{m_2}{\omega^2} + \dots\right)\right|} \tag{19}$$

Equation 19 shows that, for ω exceeding a certain arbitrary minimum value, $|E^*|$ can be approximated by

$$|E^*| = |C_0| \cdot |\omega| \tag{20}$$

This approximation represents a linear relationship between $|E^*|$ and $|\omega|$ passes through the origin. This approximation is valid for values of ω as small as 0.5 radians per second.

If a similar procedure is followed starting with the expression of E* as given by Papazian, Eq. 10, it can be shown analytically that the resulting value of $|E^*|$ can be approximated by a constant for values of $\omega > N$, where N is an arbitrarily positive number.

In that case, the absolute value of E* can be expressed as

$$|E^*| = \frac{|c_0| \cdot |\omega^{4n}|}{|\omega^{4n}|} \cdot \frac{\sqrt{1 + \frac{c_1}{\omega} + \frac{c_2}{\omega^2} + \dots}}{\left|1 + \frac{k_1}{\omega} + \frac{k_2}{\omega^2} + \dots\right|} \tag{21}$$

which will lead to an approximation of $|E^*|$ given as a constant value

$$|E^*| = |C_0| \tag{22}$$

for all $\omega > N$.

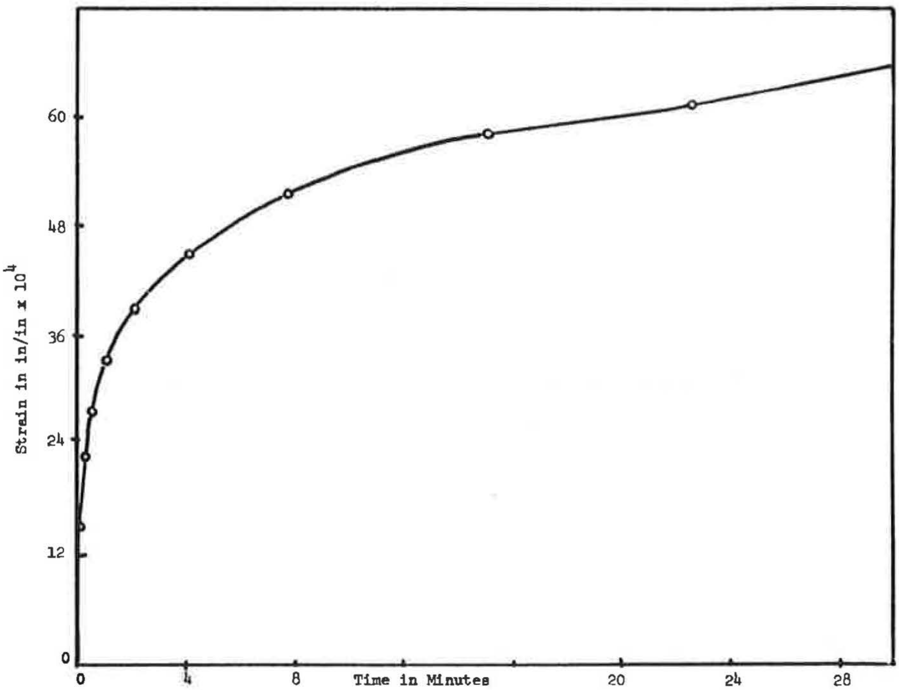


Figure 3. Typical strain-time curve as obtained by Papazian.

Comparing Eqs. 20 and 22, it can be seen that the absolute value of the complex modulus as given by these expressions is radically different. Eq. 9 for $\epsilon(0) \to 0$ indicates that E* is a linear function of frequency (ω) for all values of ω above a specified minimum value. Equation 10, for real values of $\epsilon(0)$, indicates that E* approaches a constant value independent of the frequency (ω) above a specified maximum value of ω. These findings demonstrate the critical nature of the initial portion of the creep-strain curve on the final results when determining the complex modulus. Items that appear minor when evaluating the creep-strain data—for example, the scale of the time axis of the time strain plot—can have a significant effect on the final answer obtained by this procedure.

RESULTS OF INVESTIGATION

Rheological Behavior of Bituminous Mixtures

Although the majority of the findings of this investigation are the result of experimental work, a significant contribution toward understanding the behavior of the materials under study was obtained through a theoretical analysis such as that presented in the preceding section.

This investigation indicates that the response of the bituminous mixture to applied stress is highly viscous in nature. This conclusion is based on the static tests performed during this investigation and the dynamic behavior of the material as predicted by the procedures described.

As was pointed out, the presence or absence of an initial strain in the strain-time curve of the material plays an important role in the determination of the predicted behavior of the material under dynamic load. Figures 2 and 3 show typical strain-time curves as obtained in this study and by Papazian. It can be seen that the curve obtained in this investigation shows no initial strain; however, the curve obtained by Papazian (Fig. 3) exhibits a large initial strain at t = 0. It must be observed, however, that the initial strains shown in Figure 3 may be due more to the condensed time scale than to a true initial strain. Figure 2, which shows no initial strain, is plotted over a total time interval of approximately 3 minutes, whereas in Figure 3 this same distance on

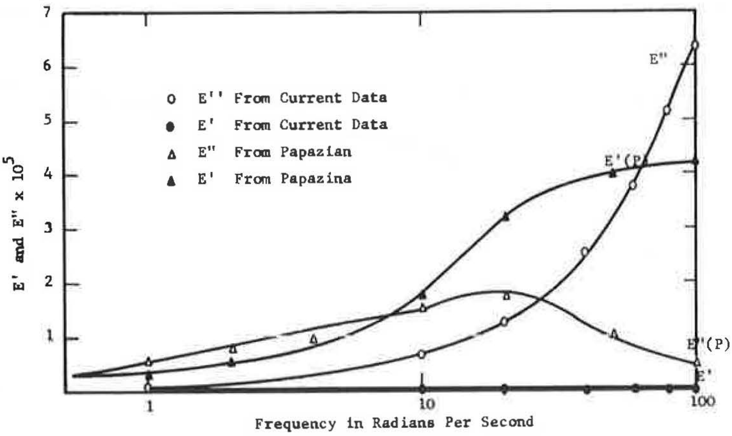


Figure 4. Comparison of real and imaginary parts as given by this study and by Papazian.

the time scale represents nearly 18 minutes. If the time scale in Figure 2 were condensed by a factor of 6 the curve would surely show an apparent $\epsilon(0)$ due simply to the inability to show small strains on the scale used. Thus the two curves in Figures 2 and 3 are more nearly identical than would be indicated by the curves shown.

Presence of an initial strain $\epsilon(0)$ (Fig. 3) indicates an immediate and elastic response of the material to an applied load, but even more important is the role that

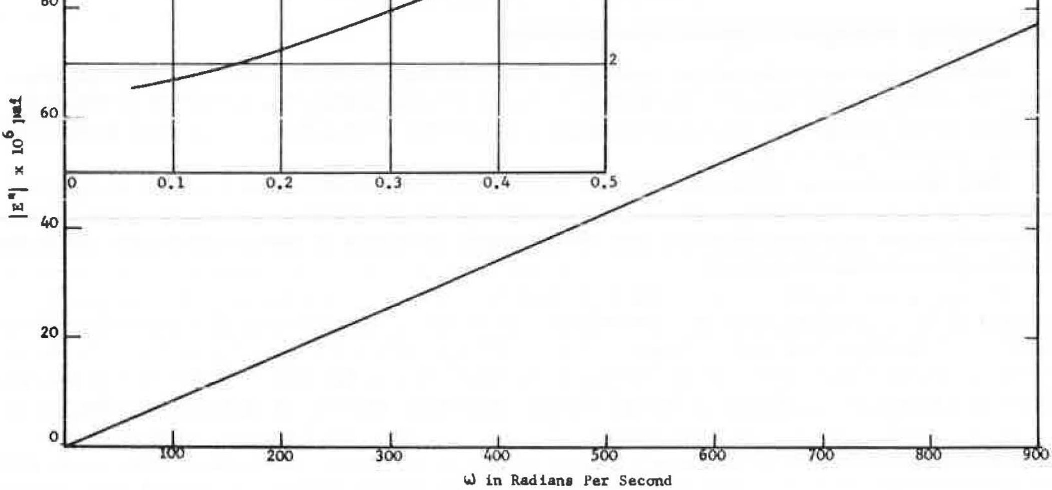


Figure 5. The complex modulus $|E^*|$ as a function of ω.

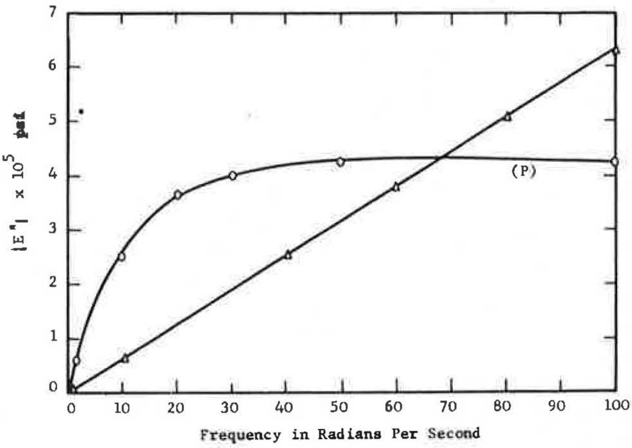


Figure 6. Comparison of $|E^*|$ as a function of frequency.

initial strain plays in determining the relationship between $|E^*|$ and the frequency ω. By virtue of the position $\epsilon(0)$ in Eq. 10, when the necessary algebraic operations are performed to compute the complex modulus E^* or its absolute value $|E^*|$, the presence of $\epsilon(0)$ in that equation makes the real component of E^* the dominant of the two components in the complex expression of E^*. On the other hand, when the initial strain is small, as was found to be the case in this study, the real part E' of the complex modulus E^* remains practically constant throughout the range of frequencies, while its imaginary counterpart E'' assumes the dominant role and increases very rapidly with an increase in frequency.

The important role played by the inital strain value $\epsilon(0)$ in determining the nature of the response of the material under study is shown in Figure 4. In Papazian's results

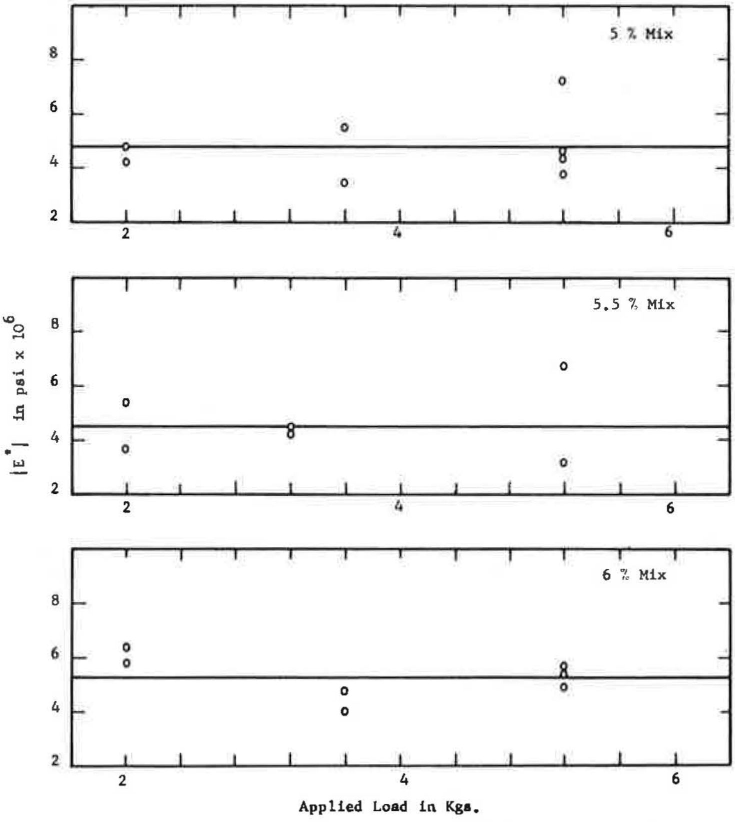


Figure 7. Effect of the applied load (I-I Soil, 70 F).

it can be seen that the real component of the complex modulus is the more important of the two components. The results of this study show, however, that the real component of the complex modulus E* is very small and remains constant throughout the range of frequency values, while the imaginary component E* increases continuously with frequency increase.

The significance of this becomes even more apparent when it is considered that the response of an elastic material is completely in phase with the applied stress, while the response of a viscous material is 90 deg out of phase with the stress (6). The real part of the complex modulus E* is, in effect, a measure of the elasticity of the material, while the imaginary part is a measure of its viscosity. It can be concluded, then, from the results of this study that bituminous mixes such as studied here have a very low elastic response and a high viscous response to applied stress. Furthermore, if the total response of the material were measured by the absolute value |E*| of its complex modulus, it would be found that |E*| will be in an approximately linear relationship with the frequency of applied load (Fig. 5). Since these values of |E*| are predicated values based on a theoretical approach with no upper limit applied, some of the values are exceedingly high. The higher values that exceed the conceivable values of the aggregate itself are due to the high projected frequencies used in the analysis.

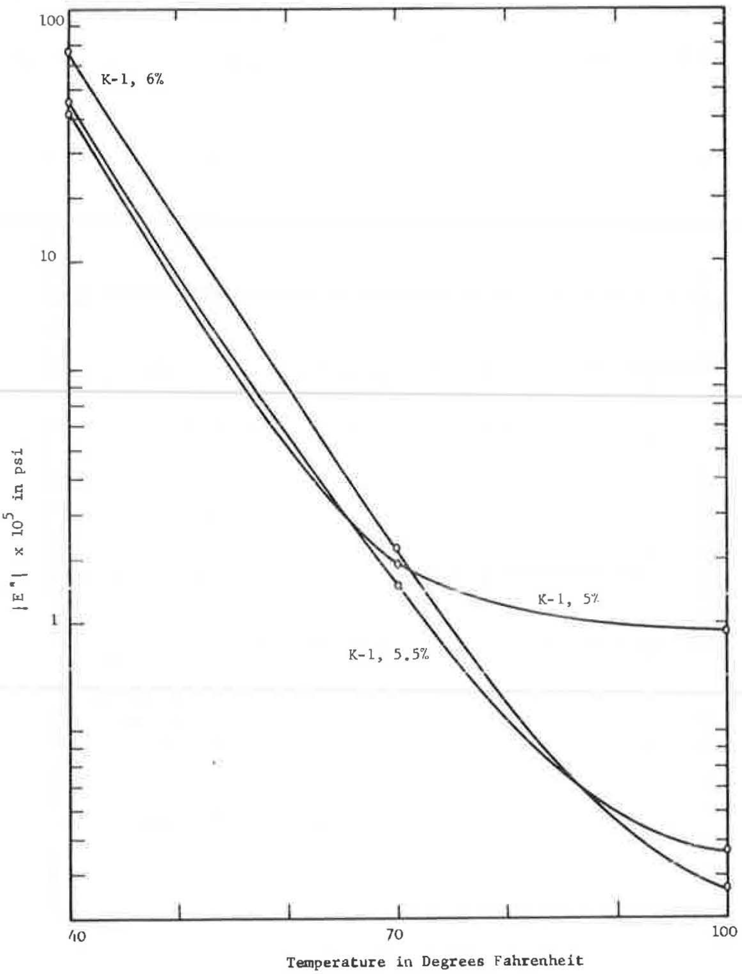


Figure 8. Effect of temperature.

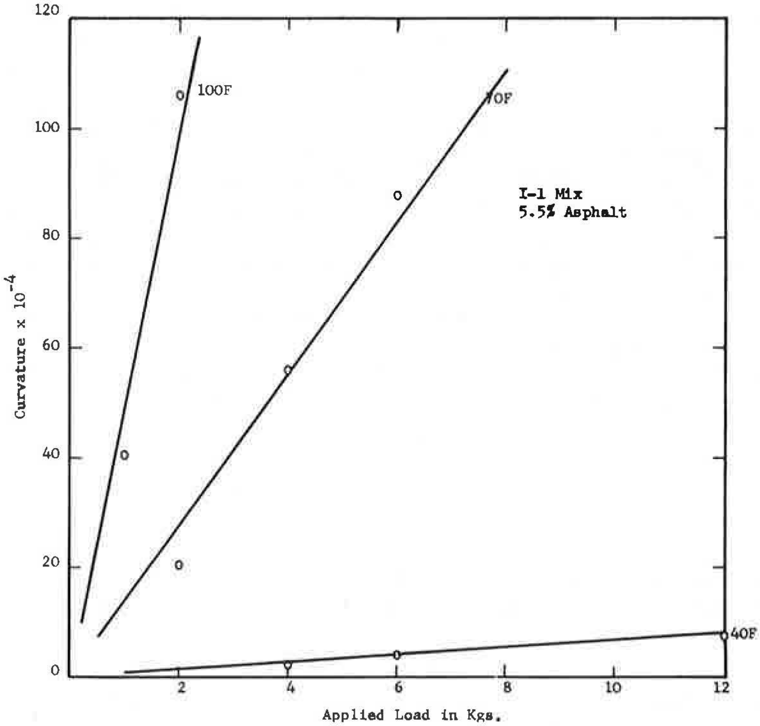


Figure 9. Effects on curvature of applied load and temperature.

These higher frequencies are well beyond values that can be expected under normal loading conditions in a pavement system. A comparison between $|E^*|$ and frequency for the current study and the results reported by Papazian (17) are shown in Figure 6. The difference between these results is due to the influence exerted by the initial strain value $\epsilon(0)$.

Effect of Applied Stress on $|E^*|$

The results from this investigation show that the complex modulus $|E^*|$ calculated for a given frequency is independent of the applied stress. These results are shown in Figure 7 for three different mixtures. Although scattering of data exists, statistical analysis performed on experimental data shows no statistically significant differences in these results. Analogous results were obtained for other mixtures tested.

Effects of Temperature and Binder Content in the Mix on $|E^*|$

The influence of temperature and the amount of binder in the mix on the rheological behavior of bituminous mixes is presented in terms of their effects on the complex modulus $|E^*|$. Representation of the influence exerted by these factors is shown in Figures 7 through 9.

The general trend for both of these factors is seen as a decrease in $|E^*|$ with an increase in either temperature or binder content. The influence of the bituminous binder content is seen to increase at the higher temperatures.

CONCLUSIONS

The literature review clearly emphasized the need to evaluate the bituminous mixtures as viscoelastic materials. Since viscoelastic materials are sensitive to rate of loading, it is necessary to evaluate these materials under variable loading conditions.

Following the lead of Papazian (17, 18), the creep-strain tests with static loading were used to develop data for predicting the response of the bituminous materials under dynamic loading. Tests were conducted to evaluate techniques used in collecting and interpreting data collected from the creep-strain tests.

Findings from this study show the need for careful interpretation of the creep-strain data to produce meaningful data for design. The characteristic shape of the time-strain curve immediately after loading has a critical influence when interpreting the data. Knowledge of the response of the material immediately after loading is highly critical because of its influence on the projected influence on the behavior of the material under variable dynamic loading conditions and because of the transient type loading that occurs in most pavements in service.

Additional data are needed to evaluate more critically the short-duration loading of bituminous materials and the use of creep-strain tests to evaluate these materials. If, as indicated in this study, the bituminous materials are more nearly viscous than viscoelastic, then efforts must be made to determine a limiting value for the complex modulus. Absolute values for the complex modulus greater than the modulus of elasticity of the aggregate portion of the mixture are obviously inaccurate. Thus, an upper limiting value must be determined for the complex modulus of bituminous mixtures.

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