Effect of Asphalt Viscosity on Rheological Properties of Bituminous Concrete

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The mechanical properties of bituminous concrete and the rheological response of asphalt greatly influence the design and construction of multilayer flexible pavement structures and are directly related to the reponse of bituminous concrete structures to traffic under various environmental conditions. The experimental phase of this research involved the testing of five different types of asphaltic concrete mixtures in which two aggregate types, two aggregate gradations, and two asphalt types are used. Correlations between asphalt viscosity, rheological strength moduli, and deformations of the bituminous mixes were developed over an extensive range of loading times and temperatures. The application of the linear viscoelastic theory and the time-temperature superposition concept to define the mechanical properties of asphaltic concrete mixtures was rigorously investigated. An equation of state to describe the load, deformation, time, and temperature-dependent behavior of asphalt concrete is presented. The agreement of the data in this experimentation provides a verification of the ability of the linear viscoelastic theory to describe the response of asphaltic concrete, as well as of the application of the derived equations of state and the time-temperature superposition concept to these materials.

•THE MECHANICAL PROPERTIES of the asphaltic concrete layers of flexible pavements and the rheological properties of the asphalt component of these layers greatly influence the design and construction of multilayer flexible pavements. The response of asphaltic concrete structures to traffic and environmental conditions is directly related to these factors. However, considerable data remain to be accumulated to establish the usefulness of viscoelastic analysis in design and to explain the mechanical behavior of asphalts and mixtures of asphalt and aggregates.

Research at The Ohio State University to date has demonstrated that, as an engineering approximation, asphalt-aggregate mixtures may be considered linear viscoelastic materials and thermorheologically linear materials (1, 2). The time- and temperature-dependent mechanical properties of bituminous concrete have also been investigated by Secor and Monismith (3) and by Krokosky and Chen (4), and this research may be used as a tool by asphalt technologists in evaluating the complex nature of such materials. Data have been obtained demonstrating the loading time and temperature dependence of such physical properties as the complex moduli, Marshall test stability, stress relaxation moduli, and creep moduli. It is possible that this rheological approach may only serve as an engineering approximation to the behavior of asphaltic concrete under definite conditions of traffic and certain ranges of temperature. However, rheological concepts provide a much higher level of approximation than the presently available elastic design theories. The objective of this research is to relate

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changes of asphalt viscosity or temperature to the mechanical properties of asphaltic concrete mixtures. The data obtained may be used to evaluate: (a) limits of asphalt viscosity which will produce specified changes of material rheological strength properties and material deformation, and (b) procedures to predict strength moduli and mixture strain based on binder viscosity over a range of loading times and temperatures.

PROCEDURE

The experimental phase of the research project involved the testing of five different types of asphaltic concrete mixtures comparable to several major categories used for road surfacing in which two aggregate types, two aggregate gradations, and two asphalt types are used. The two 85-100 penetration asphalts used in the study were obtained from different sources; one has a high temperature susceptibility as measured by microviscometer tests, and the other has a relatively low temperature susceptibility. One aggregate type is a crushed river gravel and the other is a limestone. Two aggregate gradations falling within the Ohio T-35C specifications were used, one with a maximum size of ½ in. and the other with a maximum size of ⅜ in. Test specimens, 4 in. in diameter and approximately 8 in. high, were prepared using a kneading compactor.

Constant-load compressive tests were performed on unconfined test cylinders. The experimental loads and temperatures were varied over a wide range. A standard creep testing program was used to record and analyze the instantaneous elastic, retarded elastic, and viscous deformations. Cyclic repetition of loading and unloading was also studied. Kinematic viscosity of the original asphalts used in the mixtures was measured with a sliding plate microviscometer.

Correlations between the original asphalt viscosity, mixture rheological strength moduli, and mixture deformations under load were developed for a wide range of loading times and temperatures. The application of the linear viscoelastic theory and the time-temperature superposition concept to define the mechanical properties of asphaltic concrete mixtures were rigorously investigated and validated. An equation of state to describe the stress, strain, time, and temperature-dependent mechanical behavior of the asphaltic concrete mixtures studied is presented. Two methods were employed to determine the equation of state: (a) curve-fitting procedures utilizing equations of the form of a generalized Voigt model, and (b) a Scatran computer program where the equation of state developed was in the form of sixth-degree polynomials. The equation of state developed by both methods was applied to predict the response of the material over an extensive range of loading times and temperatures.

NOTATIONS

σ = stress,

ϵ = strain,

J = creep compliance,

E = creep modulus and elastic constants,

α_T = temperature shift factor,

t = time,

T = temperature,

ζ = characteristic retardation or relaxation time,

δ = deformation,

T_0 = standard reference temperature,

k = slope of asphalt viscosity-temperature curve on semilog plot or slope of log α_T vs temperature plot,

η = dashpot constants and asphalt viscosity,

C = constant, and

e = basc of natural logarithms.

EXPERIMENTATION

The different test programs available for the investigation of the rheological properties of bituminous concrete may include constant-load creep tests, stress-relaxation tests, and direct sinusoidal-stress dynamic tests. Stress-relaxation tests are usually difficult to perform, and direct dynamic tests yield information applicable only at the frequency used in the test. The creep test, which was primarily used in this study, is relatively easy to conduct and yields information over a wide range of loading time or over a range of frequencies when transformed to the frequency domain. In the viscoelastic theory (5), creep deformation consists of instantaneous elastic, time-dependent elastic, and viscous deformation. To investigate these three components, and particularly to separate the elastic and viscous deformation from the total deformation, one must observe the rebound behavior of the material after unloading. The loading and unloading duration should be determined by comparing it with the longest retardation time. For utility and standardization of the testing procedure, a 1-hr loading and equal unloading duration were adopted in this research.

Many engineering materials exhibit the phenomenon of mechanical conditioning which can be conveniently analyzed by repetition-of-load application. Hence, the present testing program includes the following three phases: (a) constant-load creep tests, (b) creep recovery tests, and (c) repetition-of-load tests.

An independent test program to investigate the viscosity of asphalt was also performed. These experiments included the measurement of original asphalt viscosity (before mixing) by means of a Hallikainen sliding plate microviscometer.

Materials

The bituminous concrete mixtures investigated included two different asphalt types, two aggregate types, and two aggregate gradations. The two asphalts were from a Venezuela crude and California crude and have, respectively, a low and a high temperature susceptibility. The viscosities of the original asphalts are shown in Figure 1 for a range of temperatures from approximately 55 to 100 F. The two aggregate types used were a limestone and a crushed river gravel. The two gradations of the aggregates (Table 1) are within type T-35C of the Ohio Department of Highways specification. There are approximately 30 specimens in each series. An asphalt content of 5.7 percent was selected for all mixes because this value was found to be close to the optimum asphalt content for stability of the materials tested. The following series numbering system for the asphaltic concrete mixes was used:

A = Asphalt type
    1. Low temperature susceptible asphalt
    2. High temperature susceptible asphalt
B = Gradation, type T-35C
    1. Ohio minimum specification
    2. Ohio intermediate specification
C = Aggregate type
    1. Limestone
    2. River gravel

The asphalt and aggregate were proportioned on the basis of weight. Before mixing, aggregates were first heated to 300 F and kept in the oven at this temperature for at least 8 hr; then the asphalt was heated to 290 F and mixed with the aggregate by a mechanical mixer. A kneading compactor was used to compact the samples. Each mix was fed to the mold in five layers, and each layer was compacted with 25 blows. On each blow the booster exerted a compactive force of 10,900 lb. The dwell duration time for the applied load was, respectively, 4, 5, 6, 5, and 4 sec at the five layers to

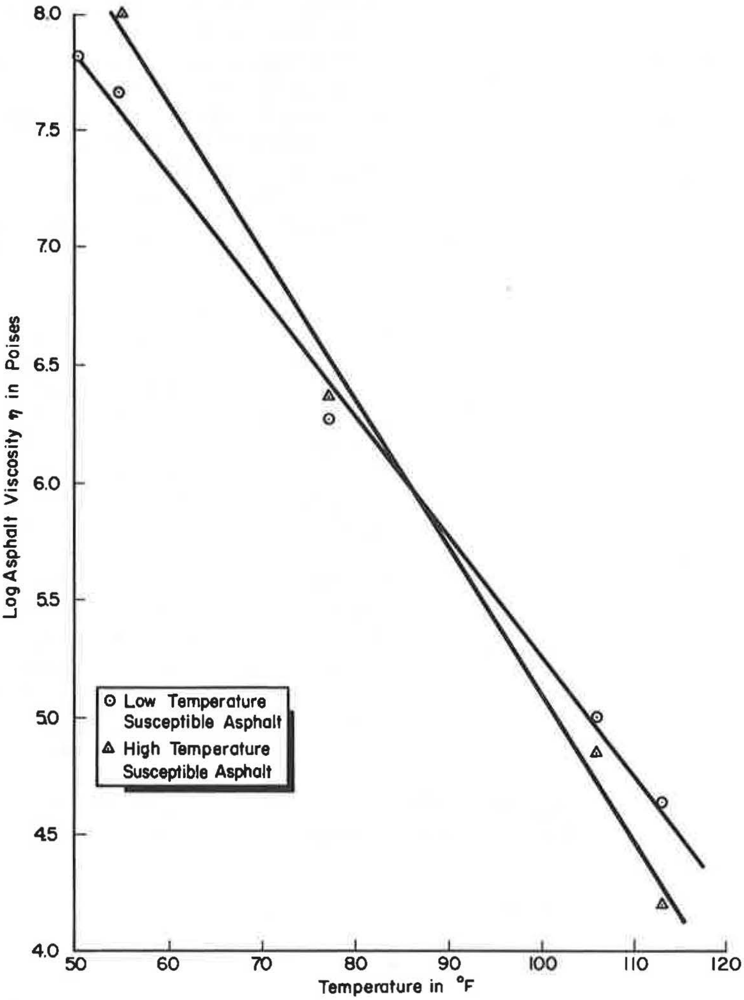

Figure 1. Asphalt viscosity vs temperature.

produce relatively homogeneous and isotropic specimens. After the compaction procedure was completed, a static load of 10,900 lb was immediately applied to the specimen and maintained constant for 5 min. The specimens prepared were 4 in. in diameter and approximately 8 in. high.

Description of Tests

Each series of specimens was investigated at three different temperatures: 41, 77, and 104 F. At each temperature, three stress levels were studied. The level of stress was different at each temperature, as indicated in Table 2.

All specimens were stored at room temperature until tested. The samples were submerged in a temperature-controlled water bath approximately 8 hr before testing. Creep experiments were also conducted at 60 and 90 F to supplement the research program. The reproducibility of the test results was also checked. As pointed out by Bland (6), the stress and strain are proportional in the linear viscoelastic range. If the strain-time curves are reduced to a curve corresponding to a standard stress by multiplying the strain-time curves by the ratio of the standard stress to the actual

TABLE 1

BITUMINOUS CONCRETE MIX PROPORTIONS

Passing U.S. Sieve	Retained on U.S. Sieve	Percent by Wt of Agg.	Percent by Wt of Total Mix	Wt/Mix (gm)
(a) Mix 1				
1/2 in.	3/8 in.	0	0	0
3/8 in.	No. 4	25.44	24.0	960
No. 4	No. 6	17.00	16.0	640
No. 6	No. 16	25.40	24.0	960
No. 16	No. 30	6.36	6.0	240
No. 30	No. 50	5.30	5.0	200
No. 50	No. 100	7.42	7.0	280
No. 100	No. 200	8.52	8.0	320
No. 200		4.56	4.3	172
		100.00	94.3	3,772
85-100 Bitumen			5.7	228
			100.0	4,000
(b) Mix 2				
1/2 in.	3/8 in.	4.24	4	160
3/8 in.	No. 4	28.60	27	1,080
No. 4	No. 6	17.00	16	640
No. 6	No. 16	24.40	23	920
No. 16	No. 30	7.43	7	280
No. 30	No. 50	6.35	6	240
No. 50	No. 100	5.30	5	200
No. 100	No. 200	5.30	5	200
No. 200		1.38	1.3	52
		100.00	94.3	3,772
85-100 Bitumen			5.7	228
			100.0	4,000

stress, a means of comparison is obtained. If the reduced strain functions obtained are within experimental error, the definitions of linearity and reproducibility of test results are satisfied. In this research the strain-time curves will form a band, rather than exactly coincide. Thus, the linearity and reproducibility of experiments are satisfied within a range of testing error. The maximum deviation for this research is approximately 15 percent, which the authors consider satisfactory for this type of experimentation. Due to inherent variation in all materials, some scatter is noted and expected in the experimental results. However, this research indicates that the mechanical response of asphaltic concrete mixtures can be approximately described by the linear viscoelastic theory. It can be rigorously argued that there are no true elastic or viscous materials (7, 8), and there is no reason to assume that a perfectly linear viscoelastic material should exist. It is important to consider whether this engineering idealization will aid highway engineers to evaluate pavement performance and assist in establishing better pavement design procedures. More sophisticated approaches are, of course, available if this engineering approximation does not prove sufficiently accurate. However, more complex methods may prove troublesome when applied to practical problems.

EXPERIMENTAL RESULTS

Creep Tests

The experimental loading data of the constant-load creep tests are shown in Figures 2 through 6. Each graph contains the strain-time data of one complete series of an asphaltic concrete mixture, with each curve representing the average of six experiments, with the exception of the 60 and 90 F tests. The six tests were performed at the same temperature under isothermal conditions, but in each case two samples were tested at three different stress levels. By application of the linear viscoelastic assumption, the six individual creep experimental results were reduced to one curve corresponding to a 10-kg loading at the experimental temperature indicated. The results, reasonably close to the average strain curve of the six creep tests, verify the application of the linear viscoelastic concepts to the asphaltic concretes investigated.

TABLE 2

Temperature (°F)	Axial Stress Level (psi)		
	σ_1	σ_2	σ_3
41	26.3	52.6	78.9
77	10.5	21.0	31.5
104	3.5	7.0	10.5

Values of the creep compliance are also indicated on the right ordinate in the foregoing figures, for convenience. The creep compliance, J, is defined as the time-dependent strain divided by the constant stress. Tabular and graphical representations were used to present the results. However, it is not possible to present all the data here, and only typical results are shown.

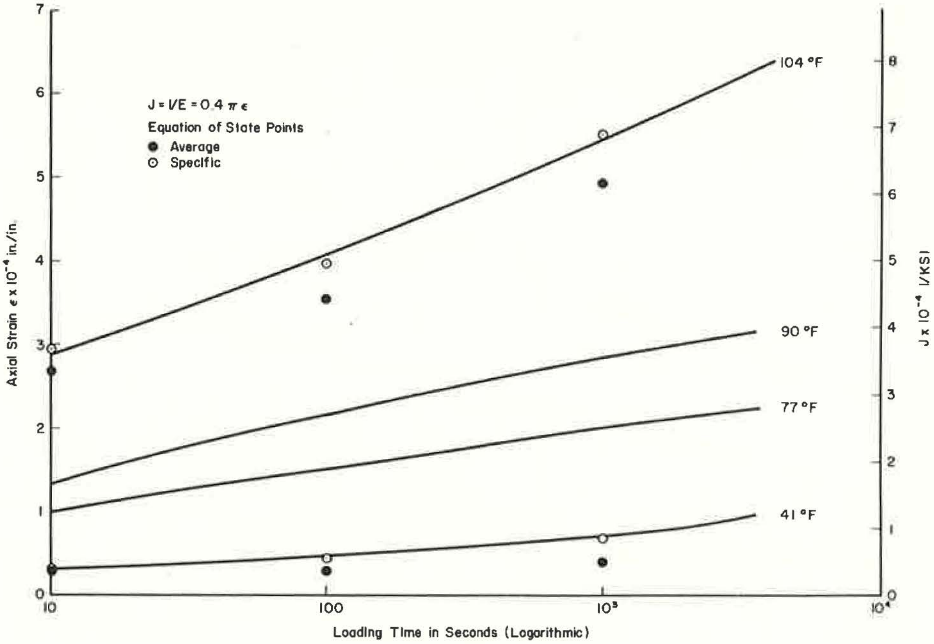

Figure 2. Strain-time data of creep tests reduced to 10-kg load, asphaltic mix 111.

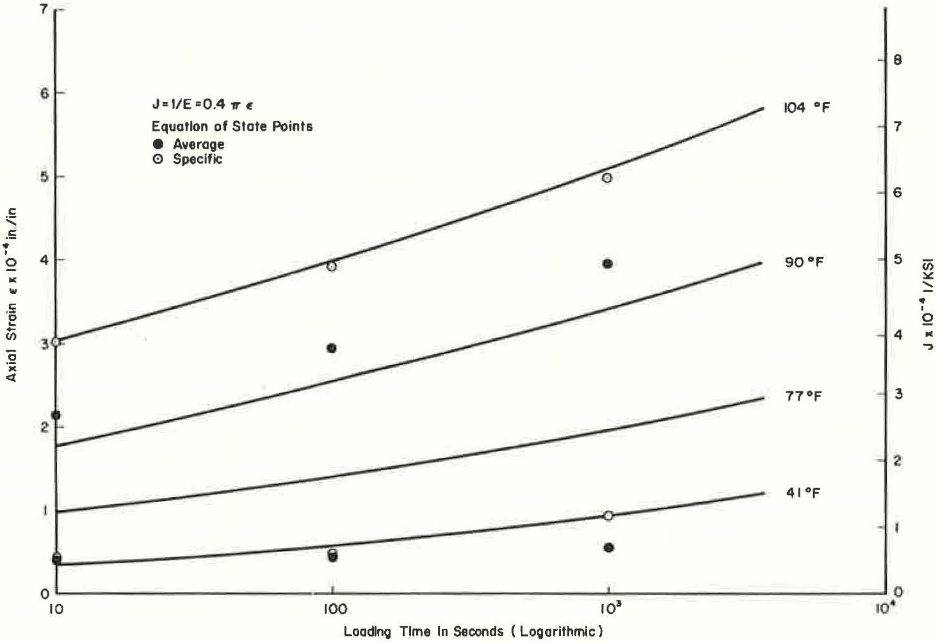

Figure 3. Strain-time data of creep tests reduced to 10-kg load, asphaltic mix 112.

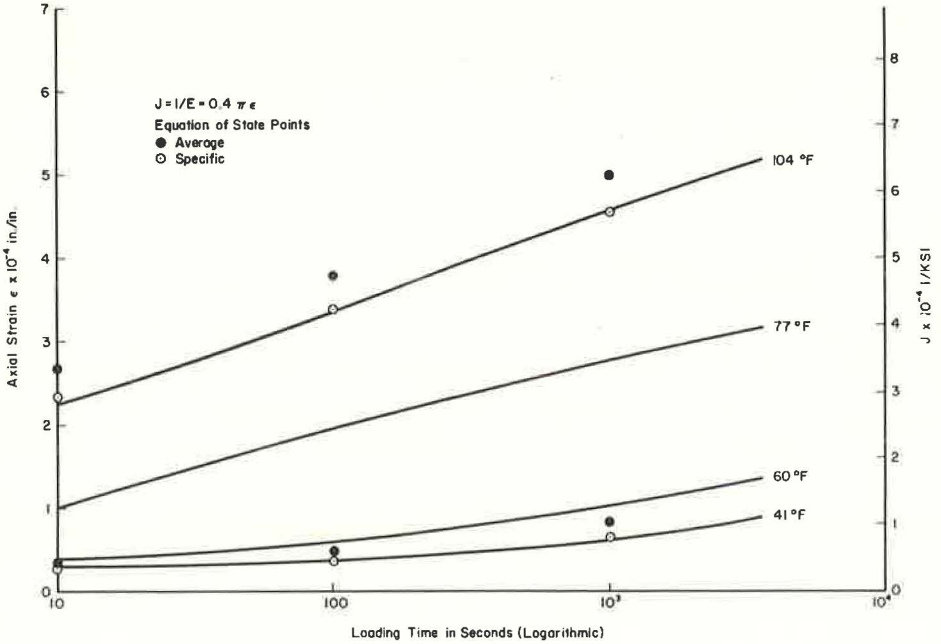

Figure 4. Strain-time data of creep tests reduced to 10-kg load, asphaltic mix 121.

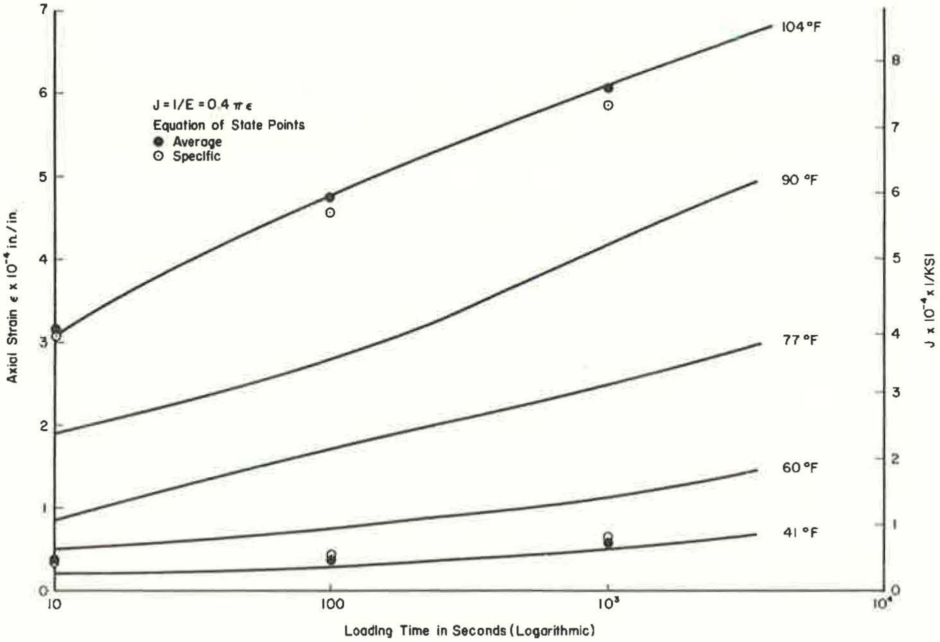

Figure 5. Strain-time data of creep tests reduced to 10-kg load, asphaltic mix 122.

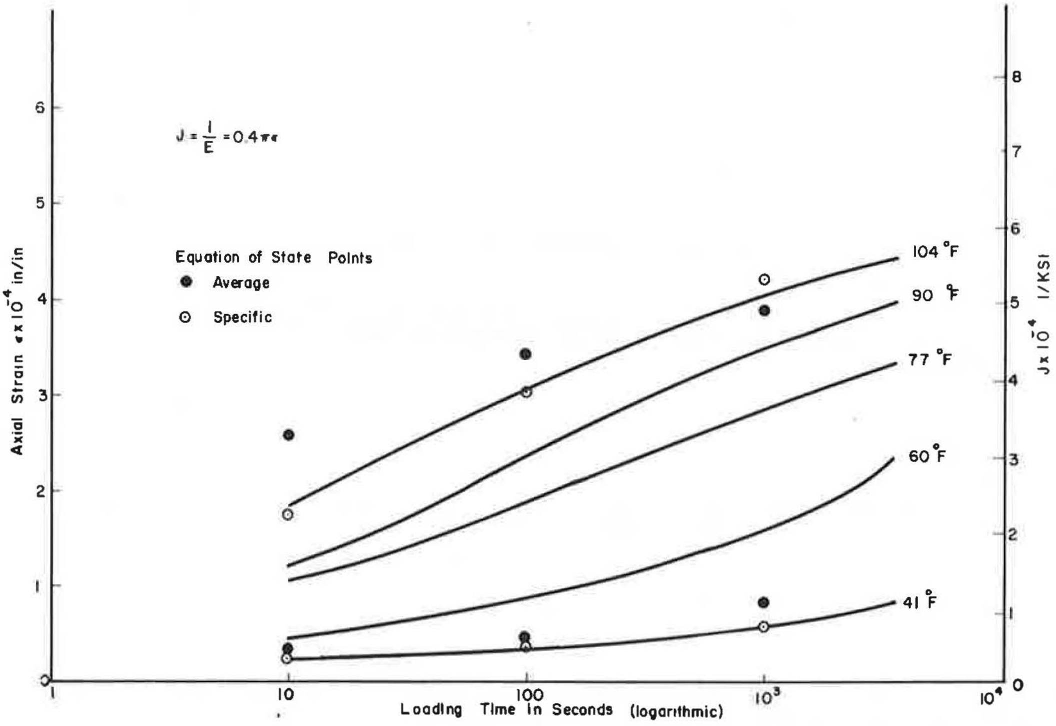

Figure 6. Strain-time data of creep test reduced to 10-kg load, asphaltic mix 222.

Repeated Loading

Figures 7 through 9 show the typical response of asphaltic concrete to repeated loading and unloading cycles and the relative creep strain for such loading patterns. The relative creep strain is defined as the total strain minus the residual viscous

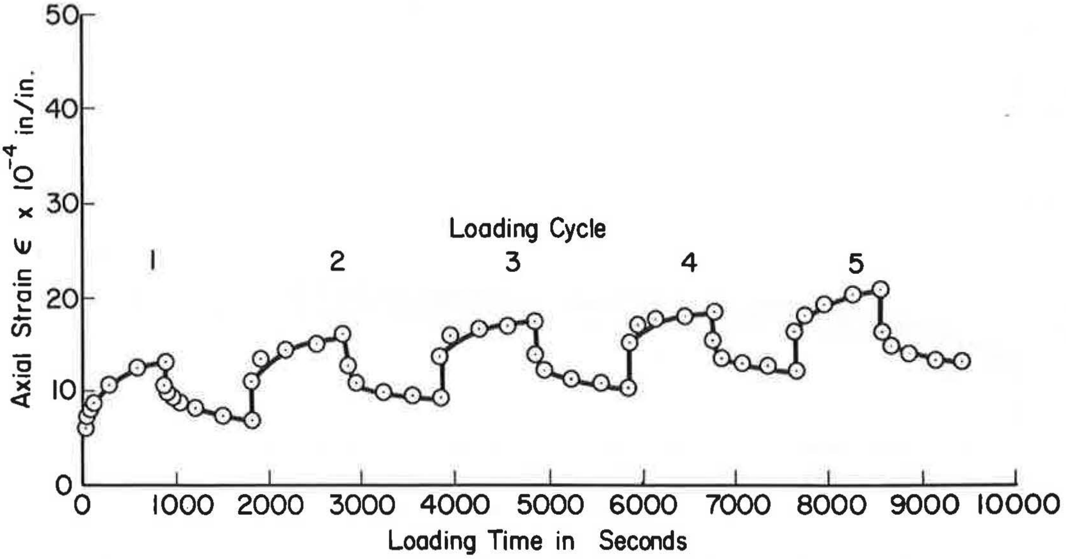

Figure 7. Creep strain under repeated 60-kg loading, 77 F, asphaltic mix 121.

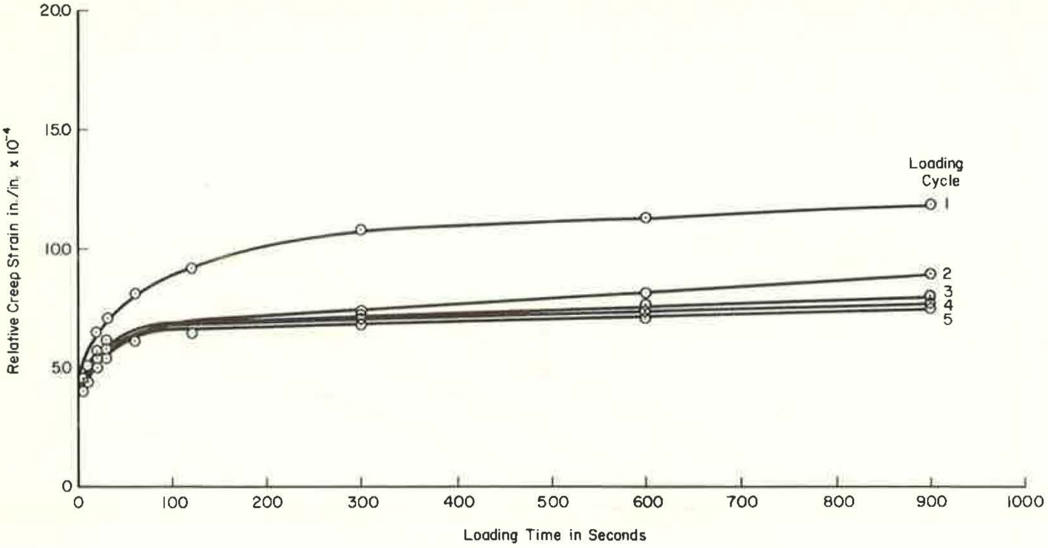

Figure 8. Relative creep strain vs loading time, 60-kg load, 77 F, asphaltic mix 121.

strain in the specimen just before loading. For all tests the relative strain for the first loading cycle had greater magnitude than in later cycles. The subsequent loading and unloading cycles had progressively smaller deviations.

The foregoing observation suggests that mechanical conditioning (9) is also possible for asphaltic concrete. From the experimental data obtained, the elastic and retarded elastic components of the total strain were found to approach a steady-state condition

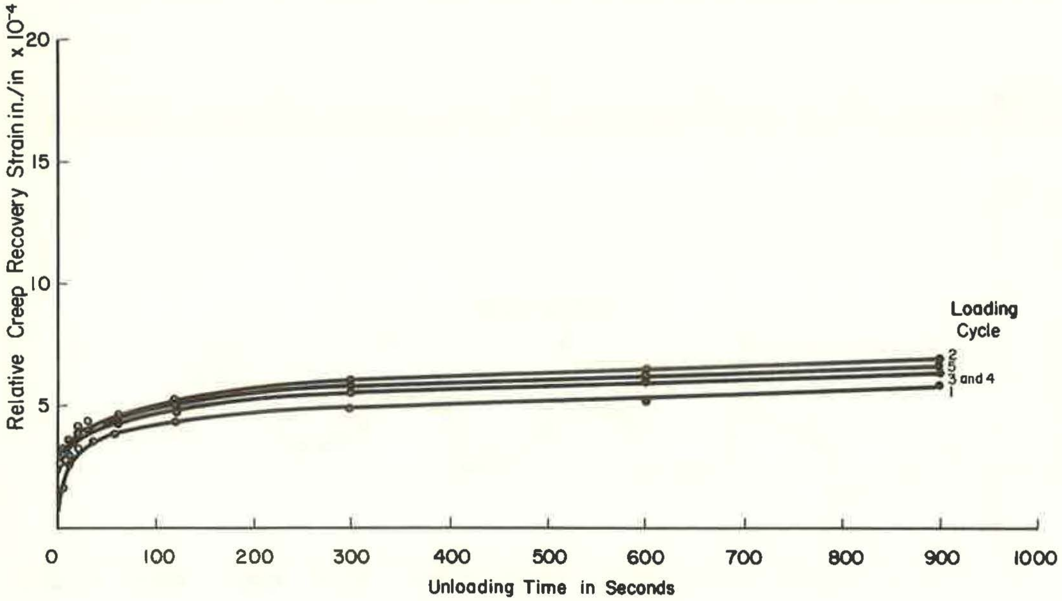

Figure 9. Relative creep recovery strain vs unloading time, 60-kg load, 77 F, asphaltic mix 121.

after approximately three or four loading cycles, but the plastic part of deformation, as expected, continued to increase at a uniform rate. After mechanical conditioning occurs, the material seems to follow the linear viscoelastic assumption to a higher degree of approximation at the conditions investigated.

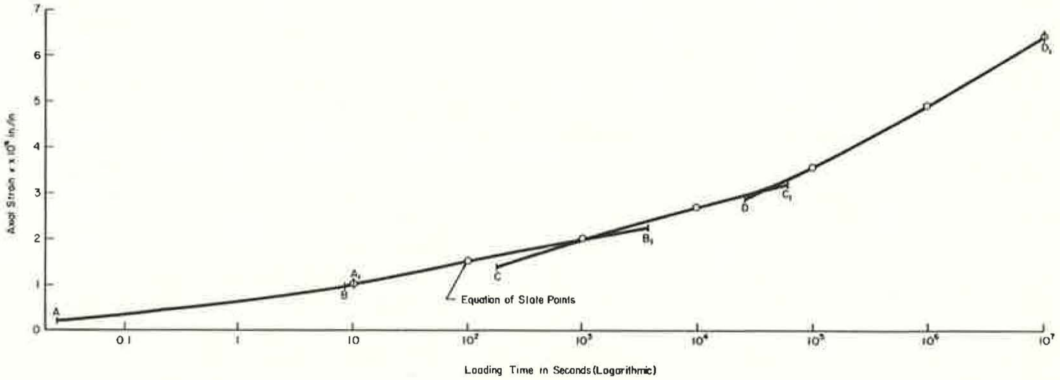

Figure 10. Composite master creep strain curve for asphaltic mix 111, 10-kg load, 77 F.

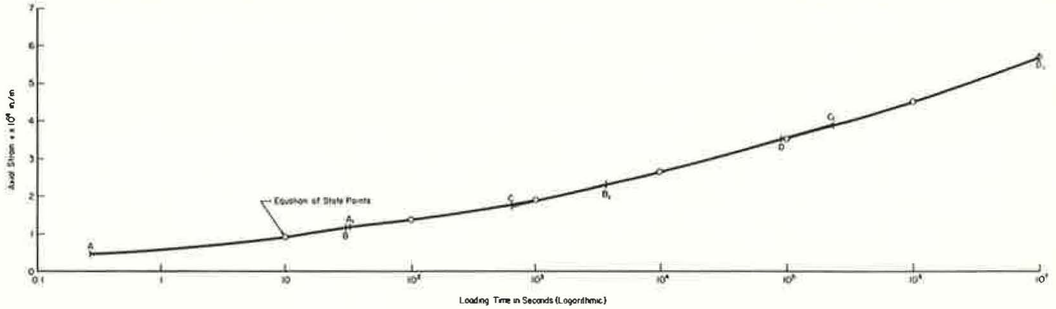

Figure 11. Composite master creep strain curve for asphaltic mix 112, 10-kg load, 77 F.

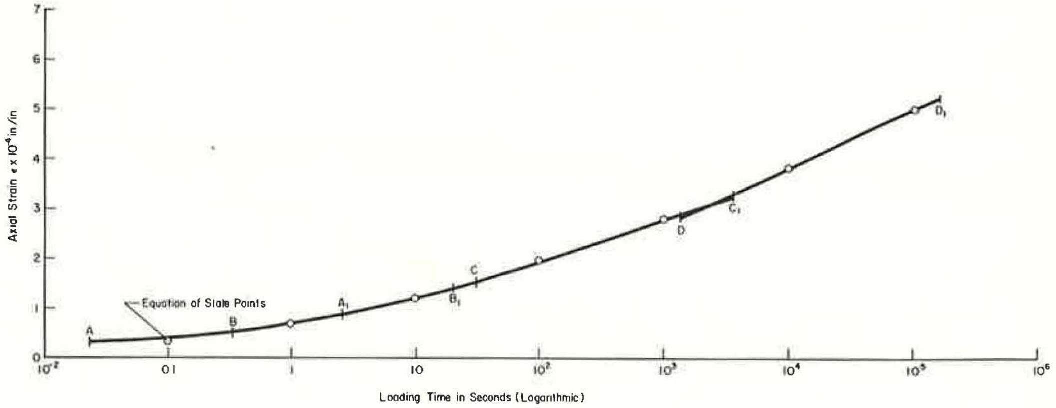

Figure 12. Composite master creep strain curve for asphaltic mix 121, 10-kg load, 77 F.

Time-Temperature Superposition Principle

The time-temperature superposition concept (10, 11, 12), was used to obtain master strain-time curves at 77 F for each series of asphaltic concrete mixes tested, as shown in Figures 10 through 14. The composite master curves were derived from the strain-time curves of Figures 2 through 6, respectively, by means of horizontal translations parallel to the time scale. Similar master strain functions can also be obtained by means of activation energy relations and a form of the Arrhenius equation (10). The curves shown represent master plots of the creep moduli over an extended portion of the time scale. By calculation of time ratios and by inspection, values were determined for the temperature shift factor, α_T, which permit horizontal shifting of the 41, 60, 90, and 104 F data to coincide with the 77 F creep data and thereby form a relatively smooth continuous master curve.

An absolute temperature factor, T_0/T, and a density factor, P_0/P, theoretically enter into the reduction scheme due to the theory of rubberlike elasticity (10) and density changes with temperature, have been omitted from calculations since they are within experimental error and approach unity. These theoretical density and temperature corrections lead to small vertical shifts of the experimental data.

The values of log α_T obtained from the tests are plotted in Figure 15. The values obtained are in close agreement with those found for another asphalt mixture similar to the test materials investigated in this research at Ohio State University (1), as shown in the figure. The solid circles indicate the sample mean, and the intervals indicate the 95 percent confidence limits of the population means (13). The straight line is the empirical regression line. The significance of the concept of reduced variables becomes more apparent when one considers that: (a) the number of experiments needed to evaluate the mechanical response of the material over a wide range

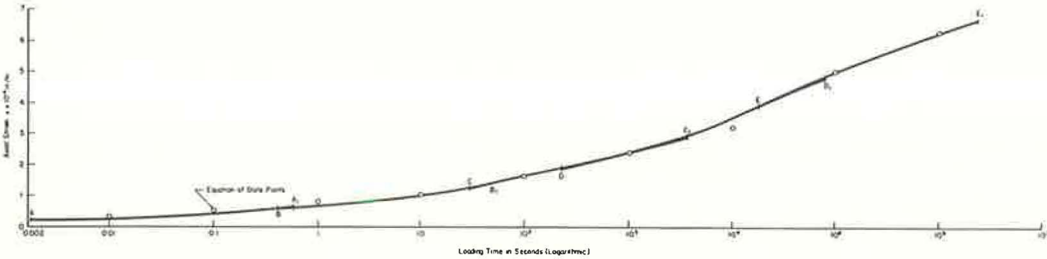

Figure 13. Composite master creep strain curve for asphaltic mix 122, 10-kg load, 77 F.

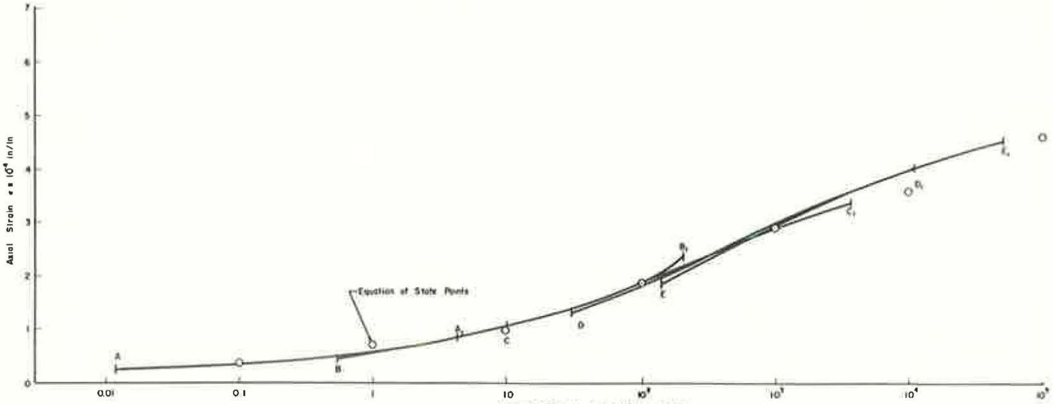

Figure 14. Composite master creep strain curve for asphaltic mix 222, 10-kg load, 77 F.

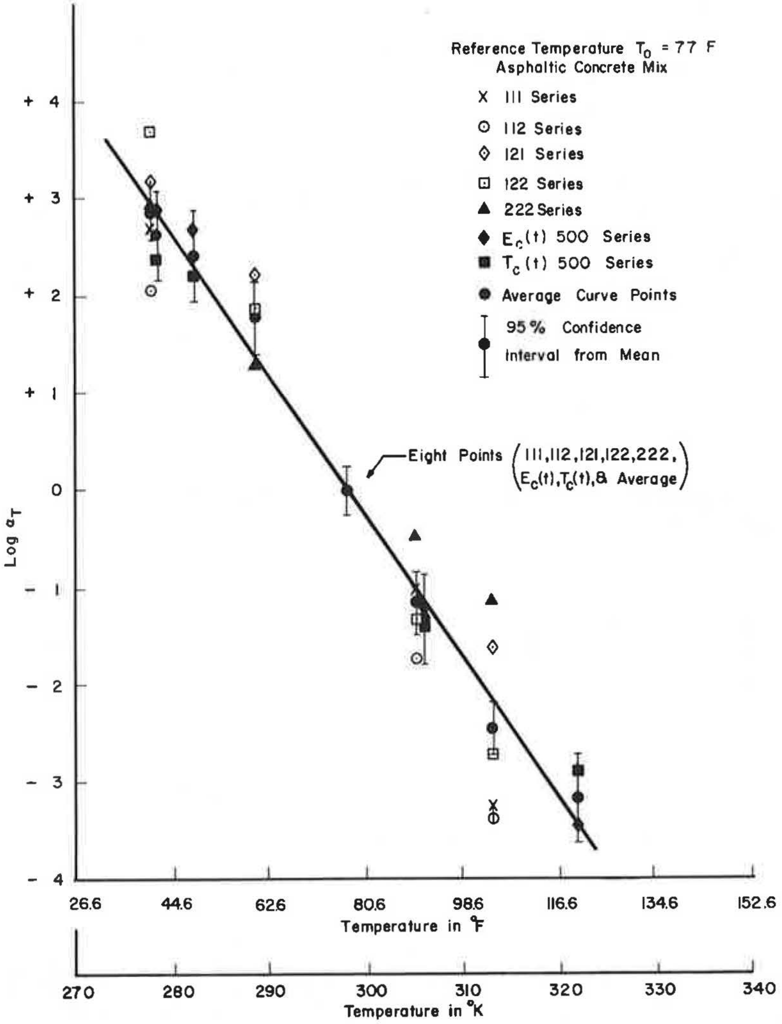

Figure 15. Temperature dependence of shift factor, a_T.

of temperature and time can now be greatly reduced; (b) the experimental data can be projected to loading times both shorter and longer than can normally be obtained experimentally; and (c) the creep compliance, creep moduli, and mixture strain can be predicted at any intermediate temperature in the experimental range for extended loading times.

Equation of State

The most important variables in investigating the mechanical response of a viscoelastic material such as asphaltic concrete are stress, strain, time, and temperature. Bituminous concrete mixes are three-phase systems and may be viscoelastic materials in which the asphalt component is the most susceptible to loading time and to environmental temperature variations. Thus, in this study, it was necessary to investigate the effect of these principal variables on the rheologic properties of the material as influenced by the asphalt phase.

A constant load applied to a linear viscoelastic material produces a deformation which increases with time. This fact can be described mathematically by the following expression (14, 15):

$$\epsilon (t) = \sigma \left[\frac{1}{E_o} + \sum_{i=1}^{n} \frac{1}{E_i} \left(1 - e^{-\frac{E_i}{\eta_i} t} \right) + \frac{t}{\eta_o} \right] \tag{1}$$

Eq. 1 shows that stress and strain are linearly related. If the stress is doubled, the resulting strain is doubled; conversely, if the strain is doubled, the resulting stress is also doubled.

A k value, defined as the slope of a straight line on a semilog asphalt viscosity-temperature plot (2), is related to the temperature shift factor, $\alpha (T)$, at a reference temperature, T_o,

$$\ln \alpha_{T_o} (T) = -k (T - T_o) \tag{2}$$

Thus, the general equation of state for the material can be written in a form similar to that of a generalized Voigt model:

$$\epsilon (t, T) = \sigma \left[\frac{1}{E_o} + \sum_{i=1}^{n} \frac{1}{E_i} \left\{ 1 - \exp \left(\frac{-E_i t}{\alpha_{T_o} (T) \eta_i (T_o)} \right) \right\} + \frac{t}{\alpha_{T_o} (T) \eta_o (T_o)} \right] \tag{3}$$

which describes the mechanical response over a range of loading times and temperatures.

Making use of Eq. 2, Eq. 3 can be written as:

$$\epsilon (t, T) = \sigma \left[\frac{1}{E_o} + \sum_{i=1}^{n} \frac{1}{E_i} \left\{ 1 - \exp \left(\frac{-e^{k (T - T_o)} E_i t}{\eta_i (T_o)} \right) \right\} + \frac{t}{\eta_o (T_o) e^{-k (T - T_o)}} \right] \tag{4}$$

which is the relation desired.

Curve-Fitted Equation

By using the graphical procedures described in an earlier report (2), the coefficients of the equations in the form of Eq. 1 were found to represent the master curves shown in Figures 10 through 14. The analytical expression for the 111 series asphaltic mix master curve under a 10-kg load at 77 F is as follows:

$$\begin{aligned} \epsilon (t) = {} & 1.49 \times 10^{-4} \left(1 - e^{-4.61 \times 10^{-7} t}\right) + 1.21 \times 10^{-4} \left(1 - e^{-4.072 \times 10^{-6} t}\right) \\ & + 5.85 \times 10^{-5} \left(1 - e^{-3.4 \times 10^{-5} t}\right) + 7.40 \times 10^{-5} \left(1 - e^{-4.18 \times 10^{-4} t}\right) \end{aligned}$$

$$+ 4.00 \times 10^{-5}\left(1 - e^{-4.36 \times 10^{-3}t}\right) + 5.63 \times 10^{-5}\left(1 - e^{-4.4 \times 10^{-2}t}\right)$$
$$+ 2.6 \times 10^{-5}\left(1 - e^{-3.815 \times 10^{-1}t}\right) + 2.57 \times 10^{-5}\left(1 - e^{-4.4t}\right)$$
$$+ 5.9 \times 10^{-12}t + 2.55 \times 10^{-5} \qquad (5)$$

The strain-time values calculated from the equations of state check very closely with the experimental values at 77 F shown in the form of master curves in Figures 10 through 14. Using the shifting factors shown in Figure 15, the k values are computed according to Eq. 2. These values are given in Table 3.

By rewriting Eq. 5 in the form of Eq. 4, the following equation was obtained for the 111 series mix:

$$\begin{aligned}\epsilon\,(t,\ T) = {} & 1.49 \times 10^{-4}\left(1 - e^{-4.61 \times 10^{-7}t \exp[k\,(T-77)]}\right) \\ & + 1.21 \times 10^{-4}\left(1 - e^{-4.072 \times 10^{-6}t \exp[k\,(T-77)]}\right) \\ & + 5.85 \times 10^{-5}\left(1 - e^{-3.4 \times 10^{-5}t \exp[k\,(T-77)]}\right) \\ & + 7.40 \times 10^{-5}\left(1 - e^{-4.18 \times 10^{-4}t \exp[k\,(T-77)]}\right) \\ & + 4.0 \times 10^{-5}\left(1 - e^{-4.36 \times 10^{-3}t \exp[k\,(T-77)]}\right) \\ & + 5.63 \times 10^{-5}\left(1 - e^{-4.4 \times 10^{-2}t \exp[k\,(T-77)]}\right) \\ & + 2.6 \times 10^{-5}\left(1 - e^{-3.815 \times 10^{-1}t \exp[k\,(T-77)]}\right) \\ & + 2.57 \times 10^{-5}\left(1 - e^{-4.4t \exp[k\,(T-77)]}\right) \\ & + 5.9 \times 10^{-12}t \exp[k\,(T-77)] + 2.55 \times 10^{-5} \qquad (6)\end{aligned}$$

Analogous equations were obtained for all the materials studied.

Eq. 6 can be used to calculate the creep strain for any temperature and loading time, provided the k values are defined. Using the k values listed in Table 3, the strains calculated by Eq. 6 and similar equations are shown in Figures 2 through 6 for temperatures of 41 F and 104 F. When the specific k values are used, the calculated strains fall almost exactly on the experimental curve. When the average k values are used, the agreement between the calculated strain and observed strain is still very good, implying that the specific k value is desirable if extreme accuracy is required.

TABLE 3

"k" VALUES[a]

Asphaltic Concrete Series	Specific		Best Line
	41 F	104 F	
111	0.1690	0.2885	0.2545
112	0.1299	0.2898	0.2017
121	0.2030	0.1390	0.1740
122	0.2361	0.2388	0.2455
222	0.1874	0.0975	0.1498

[a] Specific k values computed for particular temperatures concerned; best line k values computed for range of temperatures by drawing best straight lines through experimental points.

Computer Equations

The master curve data for the materials studied shown in Figures 10 through 14 were used to write a Scatran computer program and calculate similar equations of state, but of a sixth-degree polynomial form:

$$\epsilon (t) = C_0 + C_1 \log t + C_2 (\log t)^2 + \dots + C_n (\log t)^n \qquad (7)$$

The coefficients of the polynomial equation were calculated by an IBM 7094 computer and printed out as C_0, C_1, ..., C_6. For this research, the sixth-degree polynomial

TABLE 4

VALUES FOR POLYNOMIAL COEFFICIENTS FOR ASPHALTIC CONCRETE MIXES

Mix	Coefficients						
	C_0	C_1	C_2	C_3	C_4	C_5	C_6
111	0.641261719	0.324797884	0.055929484	-0.000518209	-0.005969534	0.001864175	-0.000137133
112	0.589549825	0.285540815	0.134473095	-0.080792851	0.029345342	-0.004377093	0.000232387
121	0.680619359	0.408324849	0.139726138	-0.014161315	-0.009319783	0.004103141	-0.000416568
122	0.706186898	0.317805842	0.049930007	0.008847243	0.002605793	-0.000233102	-0.000032063
222	0.558999084	0.339170013	0.150620632	0.017126073	-0.007738411	0.000657460	-0.000046117

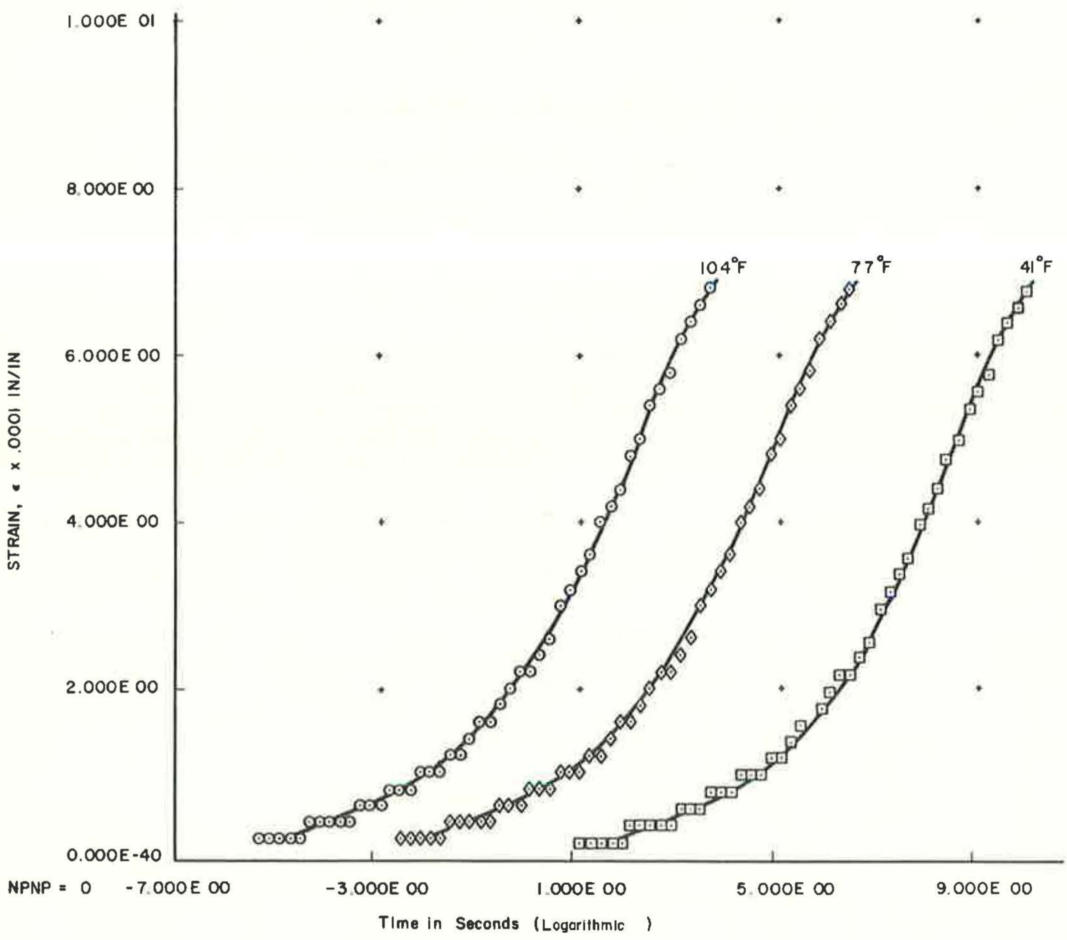

Figure 16. Computer master strain curves at three temperatures, asphaltix mix 122, 10-kg load.

equation was selected and yields a 3 percent root-mean-square error. Greater accuracy is possible by using higher order polynomials. The values of the polynomial coefficients are given in Table 4.

A second Scatran program was written to evaluate the master strain-time curves of the materials studied at any temperature in the experimental range by means of the specific temperature shift factors and the computer equations. The results were tabulated and roughly plotted by the computer as shown for the 122 series mixture in Figure 16 for the 41, 77, and 104 F master curves.

Correlation of Equation of State and Time-Temperature Superposition Concept

By comparing the strain-time values evaluated by the time-temperature superposition concept and by the equation of state, the correlation of results may be observed between both types of analyses. Values of ϵ (t), J, and E may be compared at the common experimental temperatures and loading times. The agreement between the measured and predicted strain values are shown in Figures 2 through 6 for the 41 and 104 F curves. These correlations were considered good for all experimental data analyzed. The agreement in this experiment provides a verification of the ability of the linear viscoelastic theory to describe the response of asphaltic concrete. It also provides verification of the application of the derived equation of state and the time-temperature superposition concept to these materials.

SUMMARY AND CONCLUSIONS

The major objective of this study was to relate changes of asphalt viscosity or temperature to changes in the mechanical properties of asphaltic concrete mixes. Research has shown that a correlation between these properties can be obtained. In the linear viscoelastic range of stress and in the thermolinear range of temperature, an equation of state which correlates stress, strain, time, and temperature has been derived. By a relatively few tests, this equation allows the mechanical properties of bituminous concrete to be described over a range of conditions.

For the materials and conditions studied, the following are the major conclusions of this investigation:

1. The experimental data indicate that the time-temperature superposition concept is applicable to the bituminous-aggregate compositions tested at a satisfactory level of approximation.
2. Experimentation on the phenomenological level has demonstrated that the mechanical properties of the dense bituminous concrete mixtures investigated can be expressed by the linear viscoelastic theory to a useful degree of approximation.
3. An equation of state incorporating load, deformation, time and temperature is valid for predicting deformation and strength properties of the bituminous mixes studied. This equation provides an additional, independent check of the time-temperature superposition concept used in this study.
4. Rheological experimentation is usually conducted on samples previously untested because the loading history influences the mechanical behavior of the materials. Usually, experimentation with untested specimens is all that is required to obtain the desired results in a research program. However, an asphaltic concrete exhibits mechanical conditioning and, when the material is tested, the deformation and the strength properties measured will vary with subsequent repetitions of loading and unloading. After several standard repetitions of load, the instantaneous phase, viscoelastic phase, and plastic phase of the total deformation were observed to be approximately constant for each loading and rebound cycle, suggesting that a conditioning of the samples may yield more realistic results in the case of highway pavement studies. In this research, the three rheological components of the total deformation asymptotically approached limiting values after several loading cycles, making the application of linear theory to these materials an even more valid approximation.
5. The total deformation could be separated into three components: instantaneous elastic, retarded elastic, and plastic or viscous. Evidence was obtained that the

measured instantaneous deformation of asphaltic concrete is highly dependent on testing procedure, sample preparation, and equipment used. Thus, scattering of results for this component is not unusual. The plastic component, evaluated after a specified rebound time, deviated most from the linear assumption. The retarded elastic phase was statistically linear to a high degree of approximation.

6. Application of changes in asphalt viscosities to produce desired changes in the mechanical properties of asphaltic concrete has been verified.

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