J. Materials, Conc. Struct., Pavements, JSCE, No. 544/V-32, 257-263, 1996 August

MODELING LINEAR VISCOELASTIC PROPERTIES OF ASPHALT BINDERS

Jian-Shiuh CHEN
Ph.D., Assistant Professor, School of Civil Engineering, Asian Institute of Technology (P.O. Box 2754, Bangkok 10501, Thailand)

The linear viscoelastic properties of asphalt binders are analyzed based upon two different methods: (1) nomograph and (2) dynamic mechanical analysis. The former one is an empirical procedure which has been used by paving technologists for a long time while the latter one is used to directly measure the dynamic response of materials. The application of viscoelasticity to asphalt cements is explained in terms of master curves. It is shown that data obtained from nomographs are inaccurate and misleading compared to measured data. Several models are further presented to predict the linear viscoelastic properties of asphalt binder and found that one of these models can be adequately used for asphalt binders.

Key Words: asphalt binder, linear viscoelastic properties, nomograph, master curve

1. INTRODUCTION

Engineers have traditionally dealt with two separate and distinct phases of materials: the viscous fluid and the elastic solid. Design procedures based upon these concepts have worked well because most traditional materials such as water and steel, at least to a good approximation, fit into one of these categories. Asphalt binders fall somewhere in between, depending on temperatures and loading times. At low temperatures or short loading times, the elastic behavior is observed on asphalt cements; when tested at high temperatures or long loading times, asphalt binders become viscous.

It is recognized that the viscoelastic properties of asphalt binders affect pavement performance, especially low-temperature-cracking and rutting. The demands placed on asphalt pavements are becoming much greater as the number and the gross weight of vehicles increase, and due to changes in axle configuration and the trend towards greater tire pressure. The understanding of the viscoelastic properties of asphalt binders is essential for pavement engineers to properly design asphalt concrete pavements to extend the life cycle of pavements, to reduce maintenance costs, and to minimize the impact of unanticipated pavement deterioration. This paper will present two different approaches to obtain the viscoelastic properties of asphalt binders, compare the results with each other, and evaluate the difference between these two methods. The first method is to obtain the properties through a nomograph, while the second one is to measure the properties by using the dynamic mechanical analysis. Models to predict the viscoelastic properties of asphalts will be also presented.

2. MATERIALS

Four types of asphalt binders are used in this study. These asphalts cover a wide range of different properties from soft to stiff materials, and can be considered as representative materials used in various environments of hot and cold weather. Results of the four asphalts tested by conventional methods are listed in **Table 1**. It should be noted that the data obtained from the traditional tests are the empirical properties of asphalt binders, i.e., the stress and strain as a function of temperatures and loading times are not considered in these tests.

3. NOMOGRAPH

In the early days of civil engineering, no sophisticated devices were available to measure and calculate the viscoelastic properties of asphalt binders. A common practice at that time was to use a nomograph to predict the properties. In the mid-

Table 1 Conventional Properties of Asphalts Used in This Study

Code Name	Asphalt Grade	Viscosity 60°C, P	Viscosity 135°C, cSt	Penetration 25°C, 100g, 5s	Ductility 4°C, 5cm/min, cm	Softening Pt., (R&B), °C
A	AC-10	864	283	160	150+	44
B	AC-10	1029	289	98	40	48
C	AC-5	419	179	133	137	43
D	AC-20	1992	569	64	5	52

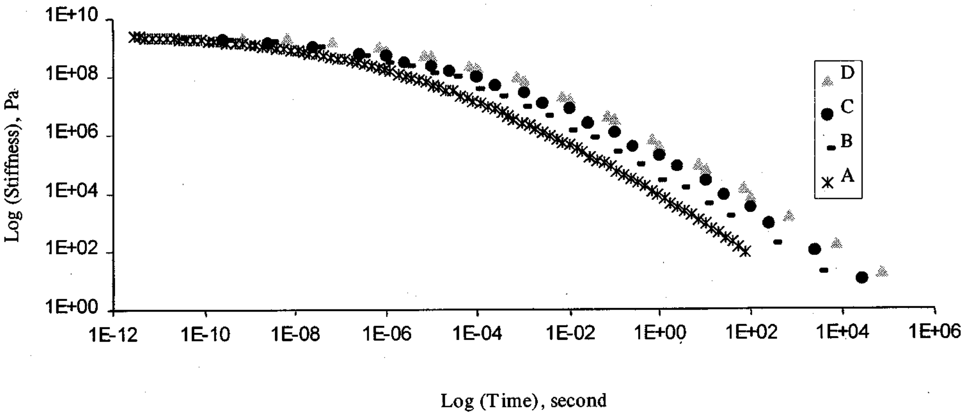

Figure 1 Master curves based upon nomograph data

1950s, Van der Poel[1] developed a nomograph to estimate the stiffness modulus over a wide range of temperatures and loading times for a variety of bitumens. The ring-and-ball softening point temperature and the penetration index are used as input parameters. Van der Poel assumed a hyperbolic shape for the stiffness as a function of time. The shape of the curve is estimated from the penetration index, which is calculated from the penetration at a specified temperature (usually 25°C) and the ring-and-ball softening point temperature. The nomograph is set up to give stiffness at a temperature relative to the softening point, at any arbitrary loading time. Van der Poel's nomograph has been widely used in pavement design and by various researchers in asphalt technology[2],[3].

One of the most-used analytical techniques employed in analyzing the viscoelastic properties of asphalts involves the construction of master curves for the stiffness. The time-temperature superposition principle, or method of reduced variables, is applied to construct such master curves[4],[5],[6]. In constructing a master curve using time-temperature superposition, stiffnesses are first collected over a range of temperatures and loading times. A standard reference temperature must then be selected; generally, 25°C is selected. The data at all other temperatures are then shifted with respect to time until the curves merge into a single smooth function. The shifting may be done based on any of the viscoelastic functions; if time-temperature superposition is valid, the other viscoelastic functions will all form continuous functions after shifting. A full set of master curves is developed from the nomograph for various values of the penetration index. The master curves based upon the nomograph for the asphalts tested in this study are shown in **Figure 1**.

Several researchers have attempted to modify Van der Poel's nomograph, including McLeod[7] and Heukelom and Klomp[8]. These latter modifications are only cosmetic, although the suggestion of using viscosity and "base temperature" rather than the ring-and-ball softening point temperature is a significant

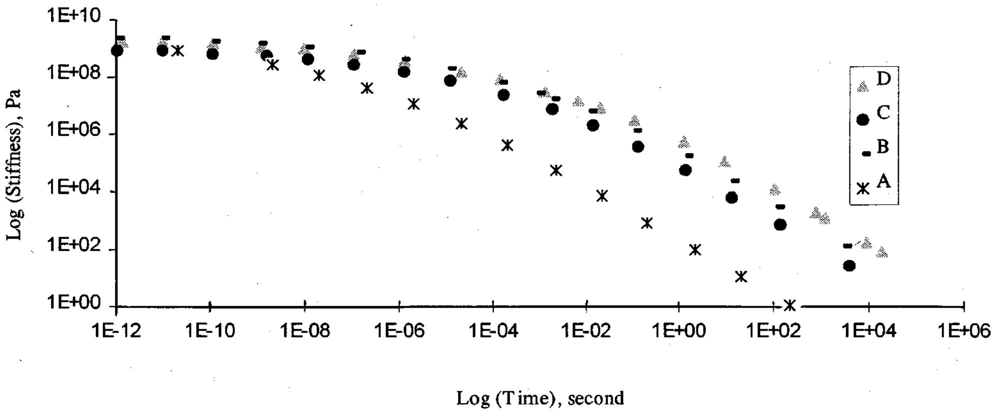

Figure 2 Master curves obtained from dynamic mechanical analysis

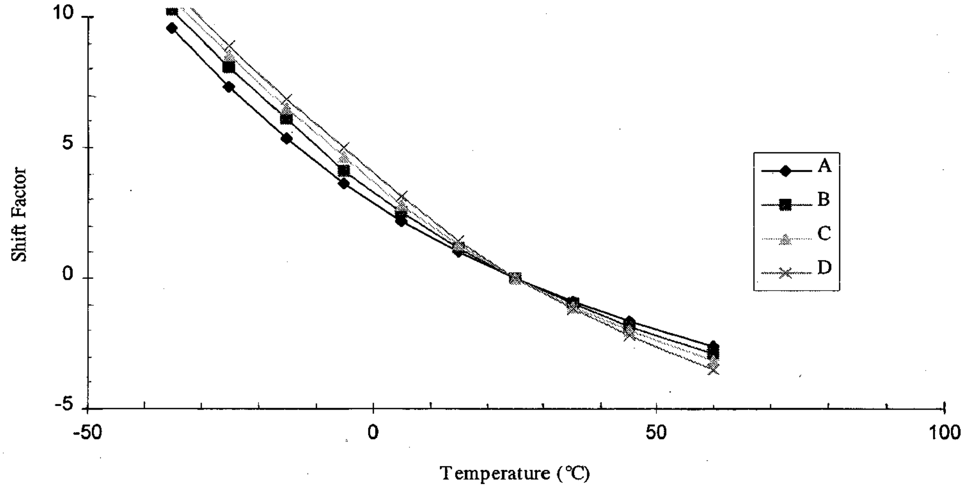

Figure 3 Shift factors as a function of temperature

deviation from Van der Poel's approach. Although the nomographs developed by various researchers offer one means of obtaining the stiffness of asphalt cement at various temperatures and loading times, questions regarding their accuracy and adequacy still remain. Direct measurements on the linear viscoelastic properties of asphalt binder are then conducted to validate the data from nomographs.

4. DYNAMIC MECHANICAL ANALYSIS

In dynamic mechanical analysis, a sinusoidal strain is applied to a specimen and the resulting stress is monitored as a function of time. This is termed as a strain-controlled testing, and is more common than stress-controlled dynamic mechanical analysis, in which a sinusoidally varying stress is applied and the strain response is measured. The dynamic mechanical properties are directly related to the creep properties, but in a mathematically complex way. Both characterizations give a complete indication of the viscoelastic properties of the material tested. Both the complex modulus and the creep compliance, in simple terms, are indicators of the resistance of an asphalt cement to flow under a given set of loading conditions.

A Rheometrics Mechanical Spectrometer, model RMS-803, was used to perform the dynamic mechanic analysis on asphalts. This device applies sinusoidal angular deflection to specimens of various geometries and sizes. At temperatures above 35°C, 25-mm diameter plates were used to perform the dynamic testing. At temperatures form 5° to 35°C, 8-mm diameter parallel plates were used. At temperatures below 5°C, the torsion bar geometry was used in the RMS-803. Two replicates of each asphalt are tested. Data are automatically acquired and reduced to engineering unit, such as complex modulus and phase angle. Measured modulus is converted to stiffness by multiplying 3 to the shear modulus obtained. After applying the time-temperature superposition, the test results are shown in **Figure 2**. It is observed from this figure that the master curves are continuous and smooth after shifting data tested at different temperatures and loading times. Thus, the time-temperature superposition is shown to be valid for asphalt binders.

The amount of shifting required at each temperature to form the master curve is called the shift factor, a(T). A plot of log a(T) versus temperature gives a visual indication of how the properties of asphalts are changing with temperatures. The shift factors for four asphalts tested are illustrated in **Figure 3**. The master curve defines the time dependence of asphalt binders, and the shift factor defines the temperature dependence of asphalt binders.

The primary response of interest in dynamic testing is the complex dynamic modulus, which is computed in strain-controlled testing using the following equation:

$$G^*(t) = |\tau(t)| \,/\, |\gamma(t)| \qquad (1)$$

where,

$G^*(t)$ = complex dynamic shear modulus at time t, Pa,
$|\tau(t)|$ = absolute magnitude of the dynamic shear stress response, Pa, and
$|\gamma(t)|$ = absolute magnitude of the applied dynamic shear strain, m/m.

As seen from the variables used in equation 1, the dynamic complex moduli are normally measured and reported in terms of shear response. The phase angle, δ, indicates the lag in the stress response compared to the applied strain. For purely elastic materials, the phase angle will be zero, whereas for purely viscous materials, the phase angle will be 90°. Thus, the phase angle is an important parameter for describing the viscoelastic properties of a material such as asphalt cement.

In reporting the results of dynamic mechanical testing, three other parameters are often used: the storage modulus $G'(t)$, the loss modulus $G''(t)$, and the loss tangent, or tan δ (tan delta). These parameters are directly related to the complex modulus and the phase angle, and can be computed through the following series of relatively simple equations. To obtain the stiffness from the shear modulus, a factor of three can be multiplied to the shear modulus and the results are shown schematically in **Figure 4**.

For the calculation of the storage modulus from the complex modulus and tan delta:

$$G'(t) = G^*(t) \cos \delta \qquad (2)$$

where,

$G'(t)$ = dynamic storage modulus at time t, Pa,
$G^*(t)$ = dynamic complex modulus at time t, Pa.

For the calculation of the loss modulus from the complex modulus and tan delta:

$$G''(t) = G^*(t) \sin \delta \qquad (3)$$

where,

$G''(t)$ = dynamic loss modulus (in Pa) at time t,

and the other variables are as defined above for equation 2 Tan delta, or the loss tangent, is calculated simply as the tangent of the phase angle, or alternatively, as the ratio of the loss to the storage moduli: $\tan \delta = G''(t)/G'(t)$.

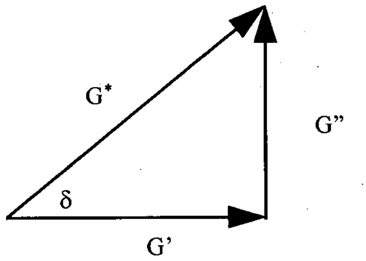

Figure 4 Relationship among different viscoelastic properties

The storage modulus, $G'(t)$, represents the in-phase

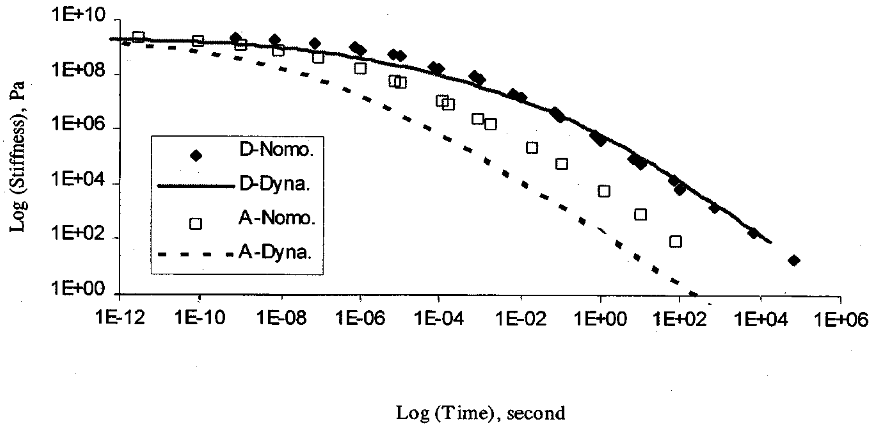

Figure 5 Discrepancy between nomograph values and dynamic mechanical data

component of the complex modulus, while the loss modulus, G"(*t*), represents the out-of-phase component of the complex modulus. These terms are sometimes misinterpreted as the elastic and viscous moduli; in reality, the elastic component of the response only represents part of the storage modulus, and the viscous response only part of the loss modulus. In addition to the elastic and viscous response, most real viscoelastic materials exhibit a significant amount of delayed elastic response, which is time-dependent but completely recoverable. In interpreting the storage and loss moduli, it should be kept in mind that both of these parameters reflect a portion of the delayed elastic response. Therefore, they cannot be strictly interpreted as elastic and viscous moduli.

In a master curve of dynamic mechanical data, one or more of the viscoelastic functions are plotted against time. At very short loading times, the complex modulus approaches a limiting value, which is the glassy modulus, or about 1 GPa as shown in Figure 2. At very long loading times, the slope of the log-log plot of complex modulus versus time approaches 1:1, which signifies that viscous flow has been reached, and that the asphalt is behaving as a newtonian fluid.

At intermediate loading times, the behavior of the asphalt changes gradually from that of a simple fluid to a glassy solid. In this intermediate region, centered around the intersection of the glassy and viscous asymptotes, most of the deformation will be of the delayed elastic type. The crossover time, t_o, is the time at which tan delta equals one.

Examining the behavior of the phase angle as a function of time, the general shape is sigmoidal. The phase angle at long loading times approaches 90°, and at very short loading time 0°. At the crossover time, the phase angle is generally very close to 45°. The phase angle in dynamic testing is directly proportional to the log-log slope of the creep stiffness curve at time 1/*t*; this conversion can be used in comparing dynamic and creep data.

With the understanding of the viscoelastic properties of asphalt binder, an effort is made to compare nomograph data with dynamic mechanical data as shown in **Figure 5**. There exits vast discrepancy between these two sets of data. The nomograph data tend to overestimate the viscoelastic properties of asphalt binders because of the inherent inaccuracy from the empirical testing procedure. It can be misleading when the pavement engineers design the pavement thickness based upon the nomograph data.

5. MODELS OF PREDICTING VISCOELASTIC PROPERTIES OF ASPHALT BINDERS

From the theoretical viewpoint, the linear viscoelastic properties of asphalt binders can be modeled by the combination of series spring and dashpot. The spring represents a linear elastic solid, and the dashpot simulates a linear viscous fluid. Several different models including the Maxwell and Voigt-Kelvin element have been used to present the linear viscoelastic properties of materials. However,

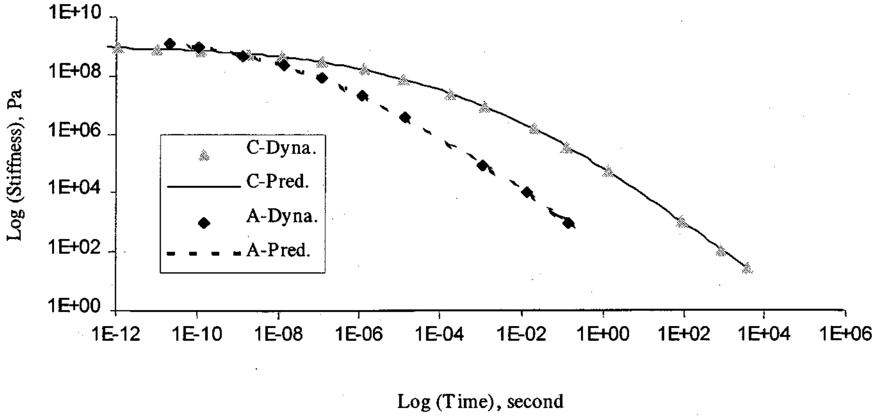

Figure 6 Master curves for measured data and predicted values

various researchers have used explicit mathematical models to characterize master curves of stiffness or complex modulus for asphalt cement.

Jongepier and Kuilman[9)] suggested that the relaxation spectra for asphalt cements are approximately log normal in shape, and they derived models for various rheological functions based on this assumption. Unfortunately, use of this model requires application of integral equations and/or transforms which can only be solved using numerical methods. Additionally, the relaxation spectra of asphalt, although close to a log normal distribution at long relaxation times, significantly deviate from this sort of distribution at shorter loading times.

Dobson[10),11)] developed a mathematical model for describing the master curve, based upon empirical relationships between the phase angle and the modulus for paving grade asphalts. The equation was for transformed time in terms of a complex function of transformed modulus. His equation does not express modulus in terms of time, but the reverse, and furthermore, this equation cannot be rearranged to solve explicitly for modulus.

Dickinson and Witt[12)] developed a model in which the master curve of complex modulus is mathematically treated as a hyperbola; several parameters can be calculated from the master curve using statistical methods which then characterize the master curve. Dickinson and Witt found that the relaxation spectra for the asphalt cements studied were somewhat skewed, and not symmetrical as would occur if the distribution of relaxation times were log normal, as suggested by Jongepier and Kuilman. There is some undesirable inaccuracy in both the glassy modulus and parameters determined from their model; a similar error should be expected in the estimated value of the newtonian viscosity. A model is developed which is rigorous in its treatment of the master curve, reasonably accurate, and mathematically simple enough to allow direct engineering calculations. For the complex modulus, the following mathematical function can be used[13)]:

$$G^*(t) = G_g[1+(t_c/t)^{(\log 2)/R}]^{-R/(\log 2)} \qquad (4)$$

where:

$G^*(t)$ = complex dynamic modulus, in Pa, at time t, second,
G_g = glassy modulus, typically 1 GPa,
t_c = the crossover time, second, and
R = the rheological index.

Figure 6 shows there is a good relationship between predicted and measured values. At intermediate to high moduli, the lines are fairly straight. But at low moduli, it appears to be a transition to a shallower slope, and narrower distribution of relaxation times. This is particularly pronounced for asphalt C. This portion of the response seems to correspond in most cases with the portion of the master curve approaching newtonian flow conditions, and is hereafter referred to as the terminal flow region, which is a standard term used in the description of the linear viscoelastic behavior of polymers and related materials. The upper portion of the curve appears to correspond to the transition region and the glassy region; since there is generally no clear distinction between these regions of behavior. It is observed that, unlike polymers, there is no plateau zone for conventional asphalt cements.

6. CONCLUSIONS

Using the empirical nomograph to predict the linear viscoelastic properties is not technically sound. Enormous errors occur when the nomograph data are used. Given the poor reliability of these nomographs and their uncertain applicability to modified asphalts, a more direct measurement on the viscoelastic properties of asphalt binder is needed. A Rheometrics Mechanical Spectrometer is applied to obtain to the fundamental properties of asphalts for the entire temperatures and loading times in this study. The application of the time-temperature superposition to asphalt binders is examined and validated. The dynamic mechanical analysis is carried out to characterize paving grade asphalts, and provides rational and accurate information concerning the viscoelastic response of such materials. Master curves and shift factors can be used to interpret the time and temperature dependence of asphalt binders respectively. Furthermore, a mathematical model is shown to be applicable and relatively simple to be used in analysis of linear viscoelastic data on paving grade asphalts.

REFERENCES

1) Van der Poel, C. : A General System Describing the Viscoelastic Properties of Bitumens and its Relation to Routine Test Data, *Journal of Applied Chemistry*, Vol.4, p.221, 1954.
2) Boannaure, F., G. Gest, A. Gravois and P. Uge: A New Method of Predicting the Stiffness of Asphalt Paving Mixtures, *Proceedings of the Association of Asphalt Paving Technologists*, Vol.46, pp.64-104, 1977.
3) Heukelom, W.: Observations on the Rheology and Fracture of Bitumens and Asphalt Mixes, *Proceedings of the Association of Asphalt Paving Technologists*, Vol.35, pp.358-399, 1966.
4) Ferry, J.D.: *Viscoelasticity Properties of Polymer*, third edition, John Wiley & Sons, New York, 1980.
5) Flugge, W.: *Viscoelasticity*, second edition, Springer-Verlag, Berlin, 1975.
6) Tschoegl, N.W.: The Phenomenological Theory of Linear Viscoelastic Behavior, Springer-Verlag, Berlin, 1989.
7) McLeod, N.W.: A 4-Year Survey of Low Temperature Transverse Pavement Cracking on the Three Ontario Test Roads, *Proceedings of the Association of Asphalt Paving Technologists*, Vol.41, p.424, 1972.
8) Heukelom, W. and J.G. Klomp: Road Design and Dynamic Loading, *Proceedings of the Association of Asphalt Paving Technologists*, Vol.33, pp.92-125, 1964.
9) Jongepier, R and B. Kuilman: Characteristics of the Rheology of Bitumens, *Proceedings of the Association of Asphalt Paving Technologists*, Vol.38, pp.98-122, 1968.
10) Dobson, G. R.: On the Development of Rational Specifications for the Rheological Properties of Bitumens, *Journal of the Institute of Petroleum*, Vol.58, No.559, pp.14-24, 1972.
11) Dobson, G. R.: The Dynamic Mechanical Properties of Bitumen, *Proceedings of the Association of Asphalt Paving Technologists*, Vol.38, p.123, 1969.
12) Dickinson, E. J. and Witt, H. P.: The Dynamic Shear Modulus of Paving Asphalts as a Function of Frequency, *Transactions of the Society of Rheology*, Vol.18, No.4, pp. 591-606, 1974.
13) Anderson, D.A., D.W. Christensen and H. Bahia: Physical Properties of Asphalt Cement and the Development of Performance-Related Specification, *Association of Asphalt Paving Technologists*, Vol.60, pp.437-475, 1991.

(Received April 13, 1995)

アスファルト・バインダの線形的粘弾性特性のモデル化

陳　建旭

アスファルト・バインダの線形的な粘弾性特性を（1）ノモグラフ，および（2）動的試験の2つの手法に基づき解析した．ノモグラフが永年に渡り舗装技術者により用いられてきた経験的な手法であるのに対し，動的試験においては材料の動的な挙動を直接測定する．アスファルト混合物の評価への適用については，載荷時間および温度の影響を補正した特性曲線により考慮する．アスファルト・バインダの線形的な粘弾性を評価するいくつかのモデルについて検討を行い，実用的なモデルを導いた．