Strategic Highway Research Program Binder Rheological Parameters: Background and Comparison with Conventional Properties

HUSSAIN U. BAHIA AND DAVID A. ANDERSON

As a result of the research conducted for the Strategic Highway Research program (SHRP), a set of new testing methods to characterize the rheological, failure, and durability properties of asphalt binders has been developed. These methods use testing devices that either are completely new or that have been used before only for research purposes. The methods also call for measuring mechanical response parameters that are not very common for asphalt pavement engineers or for many asphalt producers. The purpose is to discuss the following points: (a) the viscoelastic nature of asphalts and its relation to pavement performance, (b) the concepts behind selecting the new test methods and the new characteristic properties, and (c) how the new measured properties compare with the conventional properties. These points are addressed by providing a theoretical-conceptual background about the conventional and new tests and by comparing new and conventional data measured for a large number of asphalts that vary in their sources and their grades. The comparison identifies the advantages of the new testing methods and the need to implement the proposed testing and specification system.

One of the main objectives of the Strategic Highway Research Program (SHRP) A002A project was to identify the physical properties of asphalt cement binders that are related to pavement performance and the methods of reliably measuring these properties (*1*).

The first step to achieving this objective involved an extensive review of the literature related to asphalt materials and pavements. The review resulted in more than 500 abstracts and included information published since the beginning of the century (*2*). The review indicated that there is no lack of realization of the types of pavement failures; rutting, fatigue cracking, and thermal cracking are the main failure modes that asphalt researchers have commonly related to the physical properties of binders. Also, it was clear that age hardening is a main factor in changing the properties of asphalts during pavement service life and that thus affects performance. Moisture damage, although a major distress mode, was known to be the result of the interaction between asphalt binders and aggregate, and hence cannot be appropriately addressed by binder properties alone. The review, however, indicated that there is a significant confusion about important binder properties and which of these properties can more reliably be related to pavement performance. The confusion mainly comes from underestimation of the complexity of the binder properties and the empirical nature of the methods used to measure these properties. Although many asphalt researchers and practitioners realized the viscoelastic nature of the material and the need for fundamental rheological methods for proper characterization, few had the resources or the background to study asphalt binders by rigorous rheological methods.

H. U. Bahia, Department of Civil and Environmental Engineering, The University of Wisconsin-Madison, Madison, Wis. 53706. D. A. Anderson, The Pennsylvania Transportation Institute, The Pennsylvania State University, University Park, Pa. 16802.

The findings of the SHRP asphalt binder research indicated that to better select asphalts there is no substitute for fundamental rheological and failure characterization. The findings indicated that the existing methods are handicapped by empiricism and simplifications to levels that are not acceptable to meet the present needs of the industry. As part of the research new methods and parameters were introduced to measure more fundamental properties that can be easily related to pavement performance on the basis of sound engineering concepts. The new testing and aging methods include the dynamic shear rheometer (*3*), the bending beam rheometer (*4*), the direct tension test (*5*), and the pressure aging vessel (*6*). The new parameters include complex shear modulus (G^*), phase angle (δ), creep stiffness [$S(t)$], logarithmic creep rate [$m(t)$], and failure strain (ϵ_f).

The purpose of this paper is to provide a theoretical-conceptual background about the conventional and new tests and a comparison of properties measured by conventional and new methods for a large number of asphalts. The background and the data comparison identify the advantages of the new parameters and the importance of the properties measured with the new testing systems.

VISCOELASTIC NATURE OF ASPHALT BINDERS

The most unique behavior of viscoelastic materials is the dependency of their mechanical response on time of loading and temperature. At any combination of time and temperature, viscoelastic behavior, within the linear range, must be characterized by at least two properties: the total resistance to deformation and the relative distribution of that resistance between an elastic part and a viscous part. Although there are many methods of characterizing viscoelastic properties, dynamic (oscillatory) testing is the best technique to explain the uniqueness of the behavior of this class of materials. In the shear mode G^* and angle δ are measured. G^* represents the total resistance to deformation under load, whereas δ represents the relative distribution of this total response between an in-phase component and an out-of-phase component. The in-phase component is an elastic component and can be related directly to the energy stored in a sample for every loading cycle, whereas the out-of-phase component represents the viscous component and can be related directly to the amount of energy lost per cycle in permanent flow. The relative distribution of these components is a function of the composition of the material, loading time, and temperature.

Rheological properties can be represented either by the variation of G^* and δ as a function of frequency at a constant temperature (commonly referred to as a *master curve*) or by the variation of G^* and δ with temperature at a selected frequency or loading time, commonly called an *isochronal curve.* Although time and temperature dependency can be related by a temperature-frequency shift function (*7*), for practical purposes it is much easier to present data with respect to one of the variables. Figure 1 depicts typical rheological properties of an AC-40 and an AC-5 asphalt binder at a wide

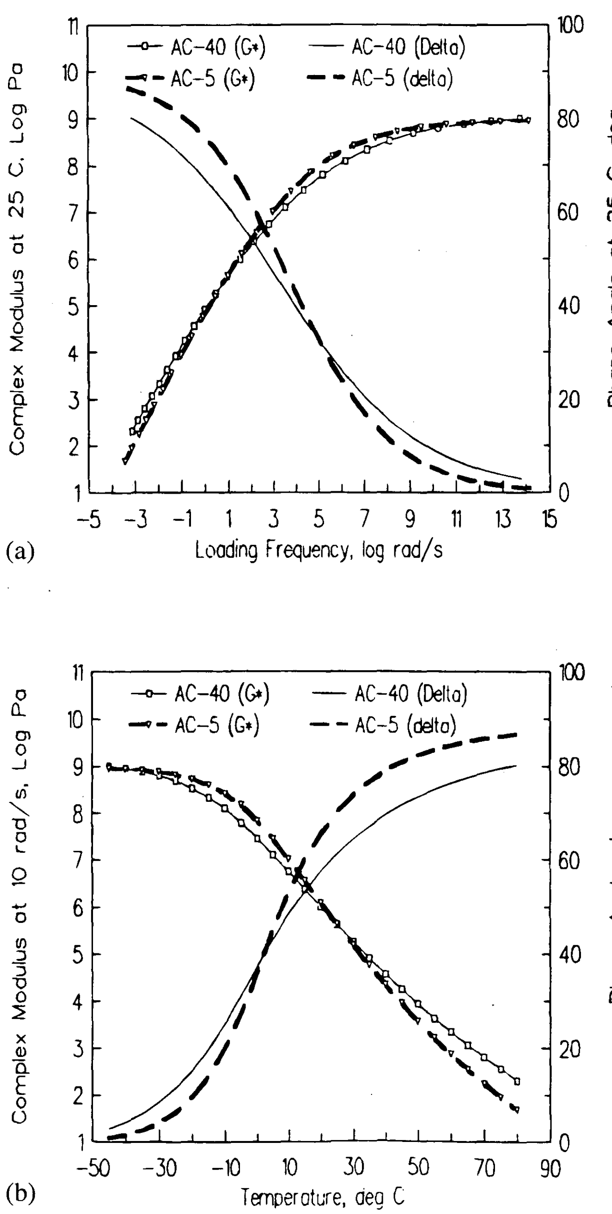

FIGURE 1 Typical rheological spectra for AC-5 and AC-40 asphalt binders: (*a*) frequency master curves; (*b*) isochronal curves.

range of temperatures and frequencies. Figure 1(*a*) shows master curves at 25°C, and Figure 1 (*b*) shows isochronal curves at 10 rad/sec.

Some common unique characteristics of the rheological behaviors of asphalts can be seen in the typical plots of Figure 1:

- At low temperatures or high frequencies both asphalts tend to approach a limiting value of G^* of approximately 1.0 GPa and a limiting value of δ of 0.0 degrees. The 1.0 GPa reflects the rigidity of the carbon hydrogen bonds as the asphalts reach their minimum thermodynamic equilibrium volume. The 0.0 value of δ represents the completely elastic nature of the asphalts at these temperatures.
- As the temperature increases or as the frequency decreases, G^* decreases continuously, whereas δ increases continuously. The first reflects a decrease in resistance to deformation (softening), whereas the second reflects a decrease in elasticity or ability to store energy. The rate of change is, however, dependent on the composition of the asphalt. Some will show a rapid decline with temperature or frequency; others will show a gradual change. Asphalts within this range may show significantly different combinations of G^* and δ.
- At high temperatures the δ values approach 90 degrees for all asphalts, which reflects the approach to complete viscous behavior or the complete dissipation of energy in viscous flow. The G^* values, however, vary significantly, reflecting the different consistency properties (viscosity) of the asphalts.

From this simplified description of asphalt properties it is clear that without the distinction between types of asphalt response in terms of total resistance to deformation (G^*) and relative elasticity (δ) and without measuring properties at the temperature or loading frequency ranges that correspond to pavement climatic and loading conditions, selection of asphalt binders for better-performing pavements is not possible. One of the main problems with the methods used currently is their failure to measure properties at application temperatures and to distinguish between elastic and nonelastic binder behavior.

ASPHALT PROPERTIES AND PAVEMENT PERFORMANCE

Figure 2 is an isochronal plot that depicts the rheological properties of an asphalt in its unaged condition and after aging in the field under a moderate climate for approximately 16 years. To relate asphalt properties to pavement performance reference can be made to four temperature zones. At temperatures above 100°C mixing and construction take place, and thus, the binder consistency needs to be controlled. At temperatures above 100°C most asphalt binders behave like Newtonian fluids, whose response is totally viscous. Therefore, a measure of viscosity is sufficient to represent the workability of the asphalt during mixing and construction of hot-mix asphalt.

At temperatures in the range of 45°C to 85°C, which are typical of the highest pavement in-service temperatures, the main distress mechanism is rutting, and therefore, G^* and δ need to be measured. A measure of viscosity alone cannot be sufficient, since viscosity measurements are done on the assumption that asphalt response has only a viscous component. For rutting resistance a high G^* value is favorable because it represents a higher total resistance to deformation. A lower δ is favorable because it reflects a more elastic component of the total deformation.

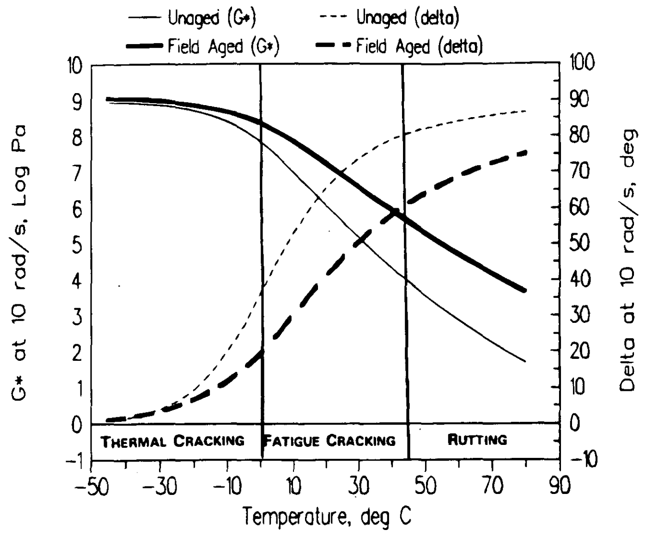

FIGURE 2 Typical rheological behavior of asphalt binders before and after aging in the field in relation to pavement main distress modes.

Within the intermediate temperature zone asphalts are generally harder and more elastic than at higher temperatures. The prevailing failure mode at these temperatures is fatigue damage, which is caused by repeated cycles of loading at levels lower than the static strength of a material. For viscoelastic materials like asphalt binders, both G^* and δ play a role in damage caused by fatigue. They are both important because during every cycle of loading the damage is dependent on how much strain or stress is developed by the cyclic load and how much of that deformation can be recovered or dissipated. A softer material and a more elastic material will be more favorable for resisting fatigue damage because the stress developed for a given deformation is lower and the asphalt will be more capable of recovering to its preloading condition. Similar to the case for rutting, a single measure of hardness or viscosity cannot be sufficient to select better-performing asphalts with respect to fatigue resistance. Rutting and fatigue damage are both functions of frequency of loading, and therefore, the rate of loading of the pavement under traffic needs to be simulated in measurement to obtain a reliable estimate of the binder's contribution to pavement performance.

The fourth and last temperature zone is the low-temperature zone, at which thermal cracking is the prevailing failure mode. Thermal cracking results from the thermal stresses generated by pavement shrinkage as a result of thermal cooling. During thermal cooling asphalt stiffness increases continuously and thus results in higher stresses for a given shrinkage strain. Simultaneously, thermal stresses relax because of the viscoelastic flow of the binder. To reliably predict the binder's contribution to cracking both the stiffness of a binder and its rate of relaxation need to be evaluated. The stiffness of the binder is directly proportional to G^*, and the rate of relaxation is directly related to δ. A lower stiffness and higher rate of relaxation are favorable for resistance to thermal cracking. As with other temperature zones, a single measure of the stiffness or viscosity of the binder is not sufficient to select better binders that will resist cracking at the lowest pavement temperatures.

This discussion of the relation between asphalt binder properties and pavement performance is further complicated by the aging phenomenon. Asphalts are hydrocarbon materials that oxidize when they come into contact with oxygen from the environment. This oxidation process changes the rheological and failure properties of the asphalt. As shown in Figure 2 the rheological master curve becomes flatter with aging, which indicates higher G^* values and lower δ values at all temperatures. These changes translate into less sensitivity of G^* and δ to temperatures or loading frequency and into a more elastic component (lower δ values). Significant oxidation effects usually appear after considerable service life. Increased G^* values and lower δ values are favorable changes with respect to rutting performance, but they are unfavorable for thermal cracking performance. For fatigue cracking the increase in the G^* value is not favorable, whereas the decreased δ value is generally favorable, depending on the type of pavement and the mode of fatigue damage.

NEW PROPOSED MEASUREMENTS AND PROPERTIES

The properties that are proposed for the new SHRP binder specification were derived and selected by addressing each type of pavement failure, understanding the failure mechanism, understanding the contribution of the binder to resistance to that failure, and selecting the required measure that will best reflect that contribution of the binder (*1*). The new binder specification is based on climatic conditions; the criteria that a binder must meet do not change, but the temperature at which the property is measured depends on the specific field climate and on the failure mode being considered.

Three failure modes were identified as critical pavement distress modes in which binder plays an important role: rutting, fatigue cracking, and thermal cracking. Oxidative aging and physical hardening were considered durability factors that cause changes in properties of binders and that thus affect performance. Four types of tests were selected (*8*):

- The rotational viscometer, to measure flow properties at temperatures that mimic temperatures at which the pumping and mixing of binders occur.
- The dynamic shear rheometer, to measure properties at temperatures that mimic high and intermediate pavement temperatures and to mimic loading rates typical of traffic loadings.
- The bending beam rheometer, to measure properties at the lowest pavement temperatures and to mimic loading conditions that result from thermal cooling.
- The direct tension test, to measure failure properties at the lowest pavement temperatures and to mimic loading that results from thermal cooling.

High-Temperature Consistency

Although workability is not directly related to pavement distress modes, asphalt binders must be workable enough at high temperatures such that pumping, mixing with aggregates, and compaction can be done efficiently to produce the required mixture properties. To ensure binder workability the Brookfield viscometer has been selected to measure steady-state viscosity at one or more temperatures. In the binder specification the binder is required to have a maximum viscosity of 3.0 Pa · sec to ensure workability. Although the rotational viscometer is already a standard test (ASTM D4402), its use will result in two changes with respect to the existing specification practices (ASTM 3381). First, it will replace the kinematic viscosity measurement; second, a maximum limit, instead of the minimum limit required in the current specification, is specified. The rotational viscometer is more suitable for modified asphalts, which are difficult to test with the capillary tubes used for kinematic viscosity. Also, a maximum limit is more appropriate to ensure the workability of asphalts.

Contribution of Binder to Rutting Resistance

Opinions about the contribution of binder to rutting resistance differ. It is a fact, however, that soft asphalts are not used to construct pavements in hot desert climates. It is also a fact that during the past decade more and more engineers are specifying polymer-modified binders, at much higher costs, to mitigate rutting problems. Aggregate properties are without doubt very important. Many engineers, however, agree that it is not good engineering practice to ignore binder properties.

Rutting is caused by the accumulation of permanent deformations caused by the repeated applications of traffic loading. Assuming that pavement rutting is mainly caused by deformations of the surface layer, rutting can be considered a stress-controlled, cyclic loading phenomenon. During each cycle of traffic loading a certain amount of work is being done in deforming the surface layer. Part of this work is recovered in elastic rebound of the surface layer, whereas the remaining work is dissipated in permanent deformation and heat. To minimize rutting the work dissipated during each loading cycle should be minimized. For a viscoelastic material the work dissipated per cycle (W_c) is calculated in terms of stress (σ) and strain (ϵ) as follows:

$$W_c = \pi \cdot \sigma \cdot \epsilon \cdot \sin \delta$$

Rutting within the asphalt concrete layer can be assumed to be a *stress*-controlled (σ_0) repetitive phenomenon. Therefore, the following substitution can be made:

$$\therefore W_c = \pi \cdot \sigma_0 \cdot \varepsilon \cdot \sin \delta$$

since

$$\epsilon = \frac{\sigma_0}{G^*}$$

$$\therefore W_c = \pi \cdot \sigma_0^2 \cdot \left(\frac{1}{G^*/\sin \delta} \right)$$

This relationship indicates that the work dissipated per loading cycle is inversely proportional to the parameter $G^*/\sin \delta$, which is the parameter selected for the SHRP specification. The parameter combines the total resistance to deformation, as reflected by G^*, and the relative nonelasticity of the binder, as reflected by $\sin \delta$. $\sin \delta$ is the ratio of the loss modulus (G'') to the complex modulus G^*. G'' is directly related to the work dissipated during a loading cycle, and thus, its ratio to G^* gives a relative measure of the nonelastic (permanent) component of the total resistance to deformation. The logic associated with the parameter is that the contribution of the binder to rutting resistance can be increased by increasing its total resistance to deformation (G^*) or decreasing its nonelasticity ($\sin \delta$).

G^* and δ are functions of temperature and frequency of loading. Therefore, to relate the measurements to pavement conditions, the specification requires testing at the average 7-day maximum pavement design temperature and at a frequency of 10 rad/sec. The proposed measurements take into account the viscoelastic nature of the material, the climatic conditions of the specific application, and the loading condition (traffic) that is causing the pavement distress.

Figure 3 depicts the values of G^* and δ for a large number of asphalts that were tested for SHRP. All measurements were done at a frequency of 10 rad/sec, which is assumed to simulate the average frequency of a stress wave in the surface layer of a typical pavement as caused by a vehicle moving at 50 to 60 mph. Figure 3 shows no specific trend between G^* and δ values. This indicates that at a certain frequency and temperature asphalts vary significantly in their G^* and δ properties. It is therefore necessary to measure both and to consider both in estimating the contributions of binders to rutting resistance. The group of datum points to the left of the plot are data measured for polymer-modified asphalts that were formulated to increase the elasticities of specific binders. The testing was done at temperatures in the range of 72°C to 82°C. This set of data points out the importance of measuring δ to characterize the elasticity at high temperatures that may significantly contribute to resistance to rutting.

Figure 3 represents the properties of unaged binders and binders aged by the thin film oven test (ASTM D1754). For all unmodified asphalts and most modified asphalts, oxidative aging results in increased G^* values and decreased δ values. These changes result in more resistance to deformation and more elasticity, which means more contribution to rutting resistance. The initial properties of the binders (early pavement life) are therefore more critical than the aged properties, and that is why the SHRP specification minimum limits are required for $G^*/\sin \delta$ measured on the unaged and the oven-aged binders.

Figure 4 compares the new measure with the absolute viscosity. Although the figure shows that there is a fair correlation between the two measures, it indicates that there is a wide range of values of $G^*/\sin \delta$ for each value of viscosity and vice versa. For example, at a value of 2000 P, typical of an AC-20 asphalt, the value of $G^*/\sin \delta$ may vary between 1700 and 3200 Pa, which is a range of −15 to +60 percent. In fact the standard error for the estimate by using a

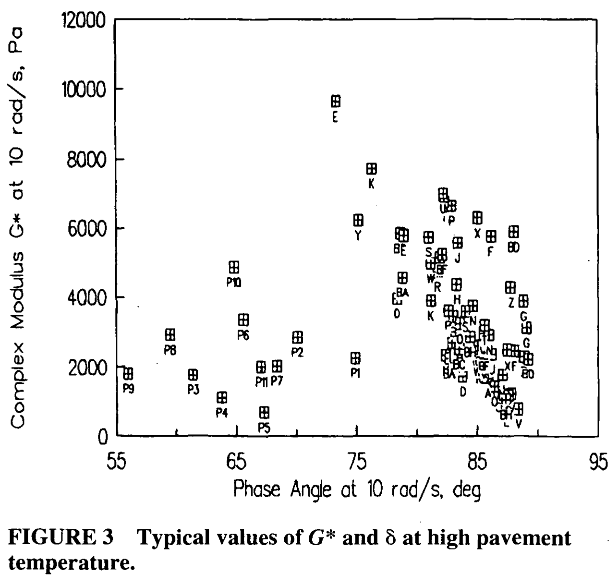

FIGURE 3 Typical values of G^* and δ at high pavement temperature.

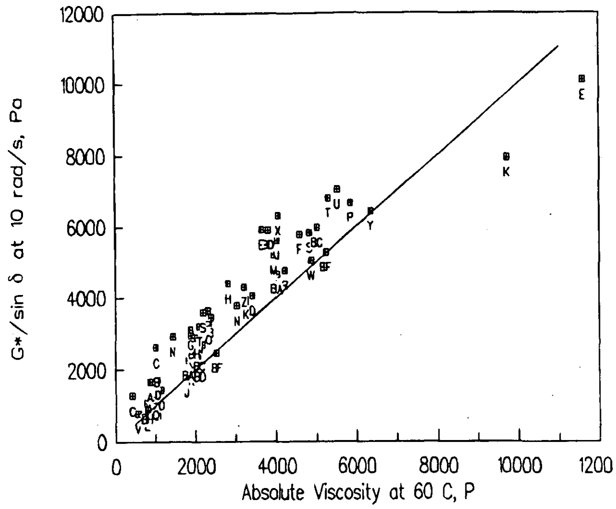

FIGURE 4 Comparison between capillary viscosity and $G^*/\sin \delta$ at 60°C.

linear relation is estimated at approximately 750 Pa, a range that cannot be considered acceptable for many engineering purposes. The discrepancy between the $G^*/\sin \delta$ and absolute viscosity is a reflection of the difference in the two measures; absolute viscosity is measured at a different shear rate, a different mode of loading, and a different strain and stress level. Absolute viscosity also does not consider the elastic response of a binder. All of these factors point out the advantages of the new parameter and indicate that absolute viscosity cannot be substituted for $G^*/\sin \delta$.

Contribution of Binder to Fatigue Cracking Resistance

As shown in Figure 2, at intermediate pavement temperatures the main distress mode is fatigue cracking. Fatigue of pavement can be a controlled-stress phenomenon (typical for thick pavement layers) or a controlled-strain phenomenon (typical of thin pavement layers). Fatigue cracking, however, is known to be more prominent in pavements with thin layers. Based on the assumption that the fatigue cracking mechanism is mainly driven by relatively large deformations of thin surface layers under traffic loading, it can be considered predominantly a strain-controlled phenomenon. The large deformations usually result from the low level of support of subsurface layers that may result from poor design and construction or because of the saturation of base layers during the spring season. Based on these assumptions the dissipated work concept can be used to derive the parameter used in the SHRP specification, $G^* \sin \delta$. For a strain-controlled cyclic loading the work per cycle equation can be rewritten as follows:

$$\therefore W_c = \pi \cdot \sigma \cdot \epsilon_0 \cdot \sin \delta$$

where ϵ_0 is the strain amplitude being applied. Since stress (σ) is related to strain by G^*:

$$\sigma = \epsilon_0 \times G^*$$

Substitution leads to the following equation, which shows that W_c under strain-controlled conditions is directly related to $G^* \sin \delta$:

$$\therefore W_c = \pi \cdot \epsilon_0^2 \cdot (G^* \times \sin \delta)$$

The work done during a loading cycle can be dissipated in one or more damage mechanisms: cracking, crack propagation, dissipated heat, or plastic flow. Although the dissipation in heat or plastic flow may be better than dissipation in cracking, heat and plastic flow are only other types of damage that may cause permanent deformation, allow faster crack propagation, or permit detrimental distortion of the asphalt mixture structure. To prevent all types of damage it is therefore best to limit the energy dissipation by limiting the value of the parameter $G^* \sin \delta$. This is the concept on which the SHRP specification is based. The logic associated with the parameter is that the amount of work dissipated is directly proportional to $G^* \sin \delta$; asphalts with lower G^* values will be softer and thus can deform without developing large stresses. Also, asphalts with lower δ values will be more elastic and thus will recover to their original condition without dissipating energy in any fashion.

Figure 5 depicts the typical range of values for G^* and δ for a large number of asphalts tested for SHRP. Similar to the rutting parameter, the values are measured at 10 rad/sec to simulate traffic loading. They are, however, measured on binders after aging in the pressure aging vessel (PAV), which has been shown to simulate long-term oxidative aging in the field. The PAV-aged condition is assumed to be more critical because for most binders it results in a significant increase in G^*, which offsets the effect of the decrease in δ. The tests are done at intermediate pavement temperatures as determined from the average of the 7-day maximum and the lowest pavement design temperatures.

The only conventional measure that is in the same temperature range of average pavement temperatures is the penetration at 25°C. Figure 6(*a*) and 6(*b*) show plots of $G^* \sin \delta$ values before and after PAV aging versus the penetration values of the unaged asphalts. The plots show that asphalts with $G^* \sin \delta$ values ranging between 0.45 and 1.8 MPa, a range of more than fourfold, can have penetration values that vary only between 50 and 60 dmm. Similarly, after PAV aging asphalts with approximately the same penetration values may have a range of $G^* \sin \delta$ values of between 1.6 and 7.0

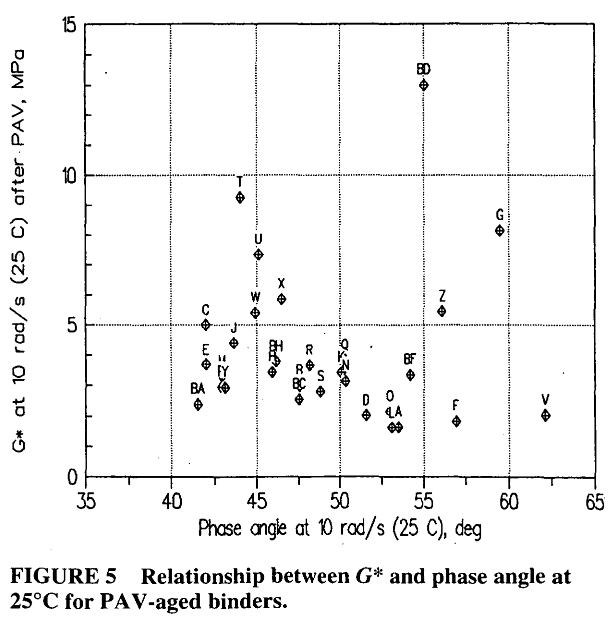

FIGURE 5 Relationship between G^* and phase angle at 25°C for PAV-aged binders.

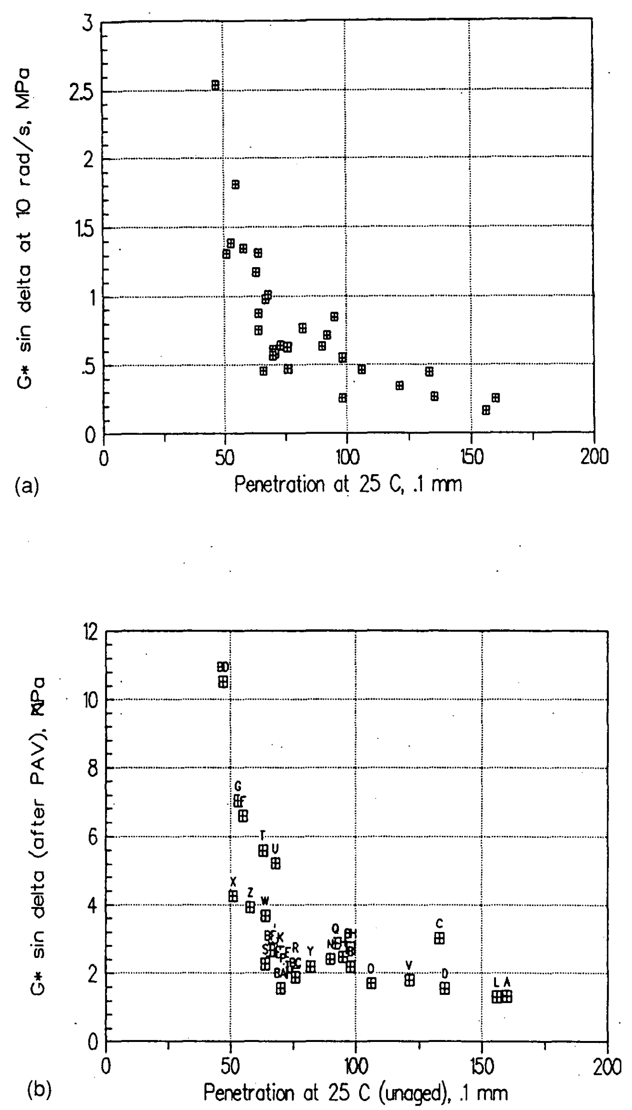

FIGURE 6 Relationship between penetration of unaged asphalts and G^* sin δ (*a*) before and (*b*) after PAV aging at 25°C.

MPa. The plots demonstrate the failure of the penetration measure to give a reasonable indication about the critical properties of asphalts. The selection of the fatigue parameter, similar to the rutting parameter, is derived on the basis of sound engineering principles; it considers the climatic conditions by testing at average pavement temperatures; it is measured by using a loading mode that simulates traffic loading; and it considers the viscoelastic nature of the asphalt material.

Contribution of Binder to Resistance to Thermal Cracking

Thermal cracking is the result of stresses developed in pavement layers because of thermal shrinkage caused by environmental cooling. Although cracking may be caused by rapid thermal cycling in relatively moderate climates, low-temperature cracking in cold regions is the predominant failure distress. During a thermal cooling cycle shrinkage of the asphalt layer in a pavement is restrained by friction with the underlying layers that either are warmer or undergo less shrinkage because of a smaller coefficient of thermal contraction. This restraint will result in the development of tensile stresses that, if not relaxed by the flow of the asphalt layer, will eventually exceed the tensile strength of the material and cause cracking. The total amount of stresses developed depends on the stiffness (resistance to deformation) of the asphalt binder and on its ability to relax stresses by dissipating energy in permanent flow. Traditionally, thermal cracking has been correlated with the stiffness of asphalts measured or estimated at certain loading times (*8,9*). Stiffness, however, does not reflect the stress relaxation ability of a binder. To be able to relax stresses an asphalt should be able to flow readily under stress and to have a less elastic component in its response. By measuring the creep response of asphalts with the bending beam rheometer the stiffness of asphalts, $S(t)$, can be measured at the lowest pavement temperatures. Also, by measuring the logarithmic creep rate, $m(t)$, the ability of an asphalt to relax stresses can be evaluated. A higher $S(t)$ reflects more stresses resulting from a given thermal strain (shrinkage), and a higher $m(t)$ reflects a higher creep rate and thus a faster relaxation rate. $S(t)$ and $m(t)$ are, however, both functions of loading time; therefore, a certain loading time must be selected to reflect pavement thermal cracking. In the asphalt literature loading times ranging between 3,600 and 20,000 sec have been correlated with thermal cracking (*2*). Such loading times are not practical for laboratory testing. To shorten the testing time the time-temperature superposition principle was used to perform tests at a higher temperature, but for a shorter loading time. During SHRP the studies of low-temperature properties have indicated that time-temperature equivalency factors are approximately the same for most asphalts (*4*). This finding was used to calculate the temperature shift required to reduce the 7,200-sec loading time, most commonly recommended in the asphalt literature, to a loading time within a 240-sec loading time range. A 10°C increase in temperature was found to be equivalent to a time shift from 7,200 sec to approximately 60 sec (*4*). In the current specification a maximum limit of 300 MPa is placed on $S(60)$, and a minimum $m(60)$ of 0.3 is required.

The logic associated with the low-temperature measures is that by placing a maximum limit on $S(t)$ the level of stresses developed in the pavement is limited, and by placing a minimum limit on $m(t)$ the rate of relaxation is kept above a certain limit. Figure 7 is a plot of $S(60)$ versus $m(60)$ for a large number of asphalts varying in source and physical properties. The measurements were done on binders aged in the PAV with the bending beam rheometer. Oxidative aging always results in increased $S(t)$ and decreased $m(t)$. Therefore, testing in the specification is required on PAV-aged binders to represent the critical aging condition. The testing is done at the minimum pavement temperature plus 10°C to reflect pavement climatic conditions. The loading condition in the pavement is also simulated by using a transient loading mode to measure the extensional stiffness. Figure 7 reflects the wide variation in $m(60)$ values for a given $S(60)$ and vice versa.

One other factor related to the low-temperature behavior of asphalts is the newly discovered physical hardening at low temperatures (*10*). Physical hardening is the increase in $S(t)$ and the decrease in $m(t)$ that occurs as a result of time-dependent volume shrinkage of asphalts. The phenomenon is caused by the deviation from thermodynamic equilibrium because of the lag of molecular adjustment behind the thermal change during cooling of the material through its glass transition temperature range. The phenomenon

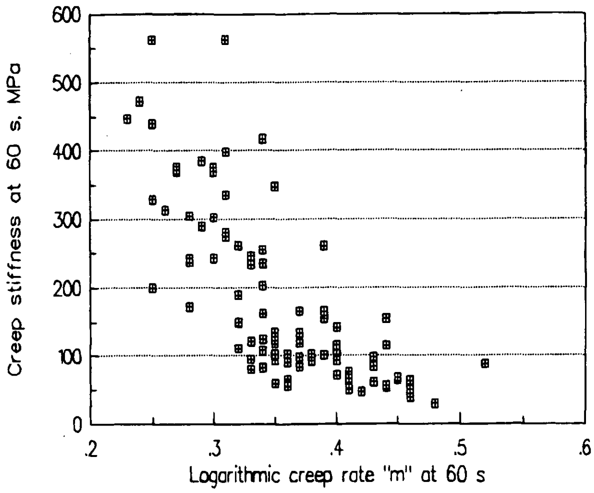

FIGURE 7 Relationship between creep stiffness and logarithmic creep rate at 60 sec for a large set of asphalts after PAV aging.

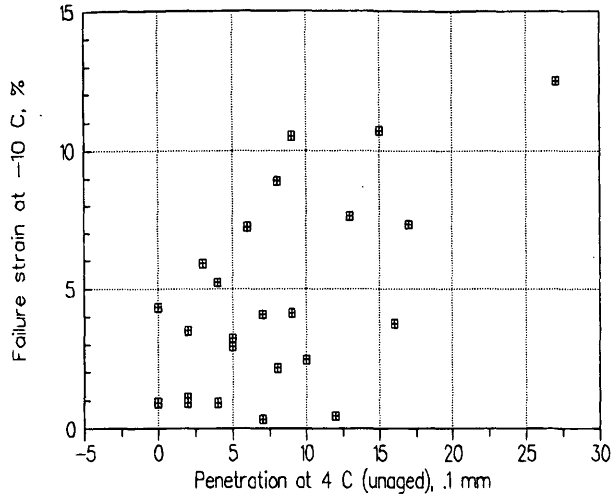

FIGURE 8 Relationship between strain at failure measured at −10°C and 1-mm/min test rate and penetration at 4°C.

resembles what is known as physical aging, which is a cause of time-dependent hardening for many plastics and polymers (*8,9*). For many asphalts physical hardening was found to increase *S(t)* by 50 to 100 percent within 24 hr. Its consequences on asphalt concrete mixture properties and pavement performance are not yet known. Therefore, the SHRP specification requires the measurement and reporting of the values of *S*(60) and *m*(60) at 1 and 24 hr to provide an indication of the potential of the binder for hardening. The reported value is intended to make engineers aware of the existence of this phenomenon and to encourage the research and engineering community to evaluate the effect of this phenomenon on pavement thermal cracking. As for the measurements used in controlling *S*(60) and *m*(60), a constant conditioning time of 60 ± 5 min is required to test all asphalts at an equal isothermal conditioning time. Physical hardening has been found to be a strong function of asphalt chemical composition and molecular structure. Its consequences, if proved to be carried at the same level as the mixture's properties, can be very important in estimating binder contribution to thermal cracking resistance.

In addition to the creep measurements the new specifications include the direct tension test, which is a true strength test. For a wide variety of materials prefailure properties do not necessarily correlate very well with the failure properties. Unmodified asphalts, however, have been shown to have failure properties that correlate well with the stiffness values at low temperatures (*1*). Based on this finding the specification does not require testing for strain at failure if the *S(t)* and *m(t)* criteria are met. For some modified asphalts the relation between the stiffness and failure properties can be different. Therefore, to accommodate those modified asphalts that may have high *S(t)* values but that can still show high strain tolerance, the direct tension test can be used to measure the strain and failure and override the *S(t)* criterion if *S*(60) is between 300 and 600 MPa. The direct tension test is another new test that gives the opportunity to directly evaluate the strain tolerance properties of specially modified binders. Figure 8 gives typical values of strain at failure for a wide variety of asphalts tested at temperatures resembling low pavement temperatures.

To compare creep measurements with conventional measures, Figure 9 shows penetration at 4°C with *S*(60) and *m*(60) measured at −10°C. At a value of *S*(60) of 100 MPa asphalts can have penetration values ranging between 1 and 10 dmm. Similarly, at a value of *m*(60) of approximately 0.35 asphalts can have penetration values ranging between 0.0 and 13 dmm. The data in Figure 9 are a clear indication of the insensitivity of penetration to the true rheological properties of asphalts at low temperatures.

SUMMARY AND CONCLUSIONS

A conceptual analysis of the viscoelastic nature of asphalt binders and the relation between their rheological properties and pavement performance has been presented. The types of conventional measures that are used at present and their failure in reflecting the crit-

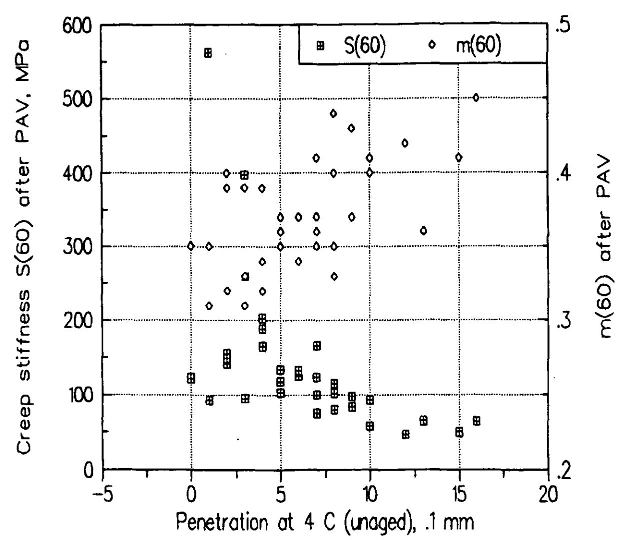

FIGURE 9 Relationship between *S*(60) and *m*(60) measured at −10°C and penetration at 4°C.

ical properties of binders were discussed. The concept on which the new testing and characterization methods introduced by SHRP are based has been presented with emphasis on how these new measures relate to pavement behavior and failure mechanisms. The conceptual analyses and the typical data comparing the conventional and the new SHRP measurements lead to the following conclusions:

1. Asphalt binders vary in their rigidities (total resistance to deformation) and their relative elasticities (distribution of that resistance between an elastic and a viscous part). For pavement applications both of these characteristics need to be measured at temperatures and loading rates that resemble climatic and traffic conditions.
2. Conventional measurements of the physical properties of asphalt include empirical measurements, viscosity measurements, and susceptibility parameters. These measurements cannot be considered reliable for characterizing the asphalt properties that are critical for pavement performance because of the empiricism involved and because of the engineering complications related to the method by which they are interpreted.
3. The new measurements proposed by SHRP are based on sound engineering principles derived from an understanding of the mechanisms of failure or damage in the pavement. They reflect the best estimate of the contribution of binders to pavement performance. They cover the main distress mechanism of flexible pavements, and they are measured under conditions that mimic climatic and loading conditions in the field.
4. No strong relationships between the new SHRP measurements and the conventional measurements exist. These two sets of measurements differ in the material characteristics that they represent and the test conditions at which they are obtained.

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REFERENCES

1. Anderson, D. A., H. U. Bahia, D. W. Christensen, R. Dongre, M. G. Sharma, C. Antle, and J. Button. *Binder Characterization and Evaluation,* Vol. 3. *Physical Characterization* Report SHRP-A-369. Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.
2. Bahia, H. U. *Bibliographies for Physical Properties of Asphalt Cement.* Report SHRP-A-626. Strategic Highway Research Program, National Research Council, Washington, D.C., 1993.
3. Anderson, D. A., and H. U. Bahia. Evaluation of Operating Conditions for Dynamic Shear Rheometers Used for Asphalt Binder Specification Testing. Presented at ASTM Symposium on Physical Properties of Asphalt Cements, Dallas/Ft. Worth, Tex., Dec. 7, 1993.
4. Bahia, H. U., and D. A. Anderson. The Development of the Bending Beam In Rheometer: Basics and Critical Evaluation. In *Physical Properties of Asphalt Cement Binders: ASTM STP 1241* (J. C. Harden, ed.) ASTM, 1994.
5. Anderson, D. A., and R. Dongre. The SHRP Direct Tension Specification Test—Its Development and Use. Presented at the ASTM Symposium on Physical Properties of Asphalt Cements, Dallas/Ft. Worth, Tex., Dec. 7, 1993.
6. Bahia, H. U., and D. A. Anderson. The Pressure Aging Vessel (PAV): A Test to Simulate Rheological Changes Due to Field Aging. In *Physical Properties of Asphalt Cement Binders: ASTM STP 1241* (J. C. Harden, ed.) ASTM, 1994.
7. Ferry, J. D. *Viscoelastic Properties of Polymers.* John Wiley and Sons, Inc. New York, 1980.
8. Bahia, H. U., and D. A. Anderson. "Physical Hardening of Asphalt Binders and Relation to Compositional Parameters," Preprints of the 204th American Chemical Society National Meeting, Division of Fuel Chemistry, Vol. 37, Nos. 3 and 4, 1992.
9. Bahia, H. U., D. A. Anderson, and D. W. Christensen. The Bending Beam Rheometer; A Simple Device for Measuring Low Temperature Rheology of Asphalt Binders. *Journal of the Association of Asphalt Paving Technologists,* Vol. 61, 1992, pp. 117–153.
10. Bahia, H. U., and D. A. Anderson. Glass Transition Behavior and Physical Hardening of Asphalt Binders. *Journal of the Association of Asphalt Paving Technologists,* Vol. 62, 1993, pp. 93–130.