

Modulus of Asphalt Mixtures— An Unresolved Dilemma

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Several moduli have been used to characterize asphalt mixtures. However, little information is available about which modulus is most appropriate to use in a given situation. This paper provides rational understanding, based on principles of strength of materials, of the moduli commonly used for structural evaluation of asphalt mixtures. Young's, shear, bulk, complex, dynamic, double-punch, resilient, and Shell nomograph moduli are discussed. The assumptions and limitations of these moduli are evaluated. It is concluded that the resilient modulus is more appropriate for use in multilayer elastic programs than are other moduli because it represents the elastic stiffness of the material after many load repetitions. Also, moduli predicted from the dynamic nondestructive testing of pavements are most representative of the in situ resilient modulus of the materials. If other moduli are used in the theoretical analysis of pavements, caution should be exercised to avoid inconsistency of assumptions.

The technology for characterizing asphaltic materials has been developed largely on an empirical basis, which has resulted in index-type values. Empirical methods of characterization are useful for comparison of materials under specific conditions. However, empirical correlations are valid only for conditions similar to those under which the values were originally developed. Further, empirical methods of characterization do not provide the information that is needed for fundamental or theory-based structural analysis of pavements. Given the continuing increase in truck weights, tire pressures, and traffic volumes and the fast deterioration of the nation's highway system, a more rational philosophy of asphalt concrete characterization is needed for optimal pavement design.

Several test procedures and theories for determining the moduli of asphalt mixtures are available in the literature. Among these moduli are Young's modulus, resilient modulus, complex modulus, dynamic modulus, and modulus obtained from the Shell nomograph. According to Brown and Barksdale (1), the term "modulus" has been "loosely" used in the literature on pavement, and the term "elastic stiffness" has been recommended. In addition, different test conditions, such as load frequency, magnitude, and duration and equipment type, may result in different values for the same modulus and for the same material. Little information, however, is available about which test method is most appropriate to use under specific conditions. Even though reasonably accurate values of test results may be obtained in the laboratory under carefully controlled conditions, extreme care must be exercised in understanding the basic nature of the test and in incorporating the test

data into mechanistic design procedures. Unless such understanding is developed, arbitrary and inconsistent moduli may be selected by different researchers, and the dilemma will remain: "which modulus is suitable to use under such conditions?"

The objective of this paper is not to list various moduli used to characterize asphalt mixtures but to provide a rational understanding of the moduli that are commonly used for structural evaluation of asphalt mixtures. A number of moduli are defined and evaluated, and the relations between these moduli and material linearity, elasticity, and viscoelasticity as well as recent mechanistic methods of pavement evaluation are discussed. The paper is intended to clarify the definition and use of terms and procedures.

STRESS-STRAIN RELATIONSHIP

A material is said to be perfectly elastic if strains completely appear and disappear immediately on application and removal of stresses. This definition does not imply a linear stress-strain relation. Effects of temperature are usually neglected in the theory of linear elasticity. In the classic theory of linear elasticity, a material can be fully characterized by two constants. These are usually Young's modulus of elasticity and Poisson's ratio.

On the other hand, viscoelastic materials exhibit a combination of elastic and viscous (time-dependent) responses. As a minimum, a modulus, Poisson's ratio, and a time-dependent term are required to describe their response. Viscoelastic materials are usually highly temperature dependent. Time-dependent responses such as creep and relaxation are typical of viscoelastic materials.

The responses of asphaltic mixes are time and temperature dependent and consequently they should be analyzed as such. Under some special conditions, however, this behavior can be approximately considered as elastic, and reasonable solutions of stresses and deformations can be obtained. It is, therefore, justifiable to employ the theory of elasticity and indicate the usefulness as well as the limitations of its application. In other cases, the theory of viscoelasticity can also be used to explain the time-dependent response of material. The choice between the two theories depends on the intended use of the results and the level of accuracy required in the analysis.

A typical stress-strain diagram for an asphalt concrete specimen monotonically (statically) loaded and unloaded during an unconfined compression test is shown in Figure 1. A small concave upturn of the curve at the beginning of loading is usually encountered because of voids (2, 3). Figure 1 shows

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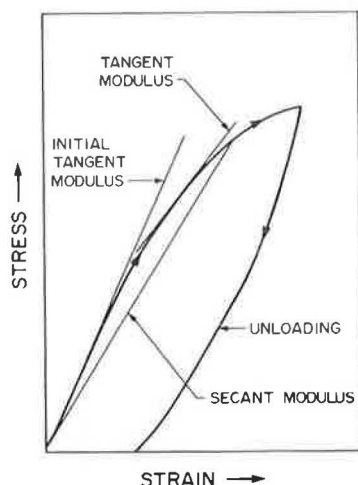


FIGURE 1 Typical unconfined compression stress-strain curve for asphalt concrete.

that asphalt concrete is a nonlinear inelastic material. The stress-strain relation depends on the rate of load application and is largely temperature dependent.

Although the monotonic (static) uniaxial compression test is commonly used to characterize soils and portland cement concretes, it has been used for asphalt concretes on a very limited basis. Likewise, the monotonic triaxial load test has not gained wide acceptance among researchers in the asphalt concrete area (4). Some of the reasons for not using the monotonic unconfined compression or triaxial load tests follow:

1. The test results are largely dependent on the rate of load application; therefore rational data interpretation is not simple;
2. Preparing the required large-sized specimens and running the test are difficult;
3. Controlling the test temperature is difficult;
4. The nonrepetitive nature of the monotonic load test does not simulate traffic load; and
5. Empirical tests such as Marshall and Hveem tests predominate.

Repetitive load-type laboratory tests have recently been developed in an attempt to simulate traffic loads. Among these tests are the sinusoidal unconfined compression tests, the triaxial resilient modulus test, and the diametral resilient modulus test. Several moduli that are not rationally understood by many highway engineers are obtained from these tests. Some of these moduli are used interchangeably without distinction and without an understanding of the relation between them and field response of material under actual traffic loading. Some of these moduli are described in the following sections.

YOUNG'S, SHEAR, AND BULK MODULI

If a material is perfectly linear elastic, Young's modulus (E) is defined as the slope of the straight line representing the stress-strain relation, and Poisson's ratio (ν) is defined as the absolute value of the lateral strain divided by the axial strain when only an axial stress is applied to a cylindrical specimen. Other elastic moduli can also be defined: shear modulus (G), bulk modulus

(K), or the Lamé constants (λ and μ). The interrelationships between these constants are (5)

$$G = \frac{E}{2(1 + \nu)} \quad (1)$$

$$K = \frac{E}{3(1 - 2\nu)} \quad (2)$$

$$\lambda = \frac{E\nu}{(1 + \nu)(1 - 2\nu)} \quad (3)$$

$$\mu = G \quad (4)$$

It should be recognized that these elastic parameters have precise meanings in the linear theory of elasticity. However, in the literature on pavement, other moduli that are descriptive of laboratory and field data have been defined.

Because the stress-strain relation of asphalt concrete is not linear (Figure 1), the term Young's modulus of elasticity can strictly be applied only to the straight part of the stress-strain curve or, when no straight portion is present, to the tangent to the curve at the origin. This is the initial tangent modulus, but it is of little practical importance. It is also possible to find a tangent modulus at any point on the stress-strain curve, but this modulus applies only to quite small changes in load above or below the load at which the tangent modulus is considered. Another modulus that can be defined is the secant modulus, which is the slope of the line from the origin to any point on the stress-strain curve. The secant modulus represents an average modulus between zero load and the load at which the modulus is determined. It should be noted that these moduli are applicable to static (or quasi-static) loading conditions as opposed to dynamic (or repetitive) traffic loading conditions.

COMPLEX AND DYNAMIC MODULI (ASTM D 3497)

When a viscoelastic cylindrical specimen is subjected to a sinusoidal axial load, the strain lags the stress as shown in Figure 2. The complex modulus is the complex quantity (i.e., real and imaginary number) that relates axial stress to axial strain in a cylindrical specimen subjected to sinusoidal loading. The imaginary part of this quantity represents the internal (material) damping property of the material, and the real part characterizes its stiffness (Young's modulus). Considerable

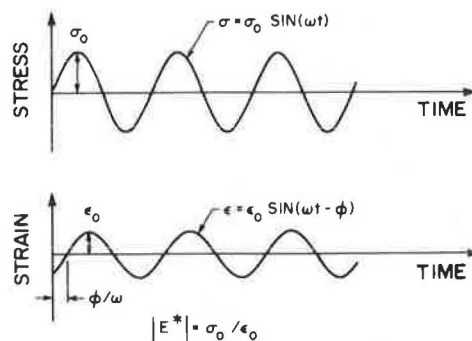


FIGURE 2 Typical plot of stress and strain versus time during the complex (dynamic) modulus test.

care is needed to carry out the requisite dynamic tests because of the hazards of resonance and inertial resistance in the sample and test equipment that may swamp the true response characteristics of the material, particularly at high frequencies. In classic elastodynamics (5), the stiffness of materials is assumed to be frequency invariant, but frequency-dependent material properties can be accommodated within such analyses by solving for each component frequency separately. Frequency-dependent material damping can be treated similarly. The complex modulus is usually denoted by E^* :

$$E^* = \frac{\sigma_0 \sin \omega t}{\epsilon_0 \sin (\omega t - \phi)} \quad (5)$$

$$= E(1 + 2i\beta) \quad (6)$$

where

- ω = angular frequency of vibration (radian/sec),
- ϕ = phase difference between the stress and the strain,
- i = unit imaginary number, and
- β = damping ratio.

The transformation from circular functions to complex numbers is accomplished by means of the Euler transformation, whence

$$\beta = \frac{1}{2} \tan \phi \quad (7)$$

and

$$E = \frac{\sigma_0}{\epsilon_0} \cos \phi \quad (8)$$

The absolute value (magnitude) of the complex modulus, $|E^*|$, is commonly referred to as the dynamic modulus. With respect to the parameters described,

$$|E^*| = \frac{\sigma_0}{\epsilon_0} \quad (9)$$

Papazian (6) has measured a substantial frequency effect on the complex modulus of asphaltic materials. If this is true, and not an artifact of the test procedure, these data should be incorporated into elastodynamic analyses of pavements. Figure 3 shows the apparatus used to determine the complex and dynamic moduli of asphalt concrete; it is essentially an electrohydraulic machine (capable of applying sinusoidal loading) and strain-measuring devices.

A different procedure for obtaining the dynamic modulus, which is known as the double-punch modulus, was used by Al-Juraiban and Jimenez (7). In this test, a 4-in.-diameter specimen is subjected to a sinusoidal load through two 1-in. cylindrical punches along the specimen axis. This load creates tensile stresses in the radial direction. The amplitude of the radial expansion is obtained at midheight of the specimen. The double-punch modulus is obtained by dividing the stress amplitude by the strain amplitude assuming linear elastic response.



FIGURE 3 Complex (dynamic) modulus apparatus.

In general, the dynamic modulus is insufficient to explain true material response because it ignores the loading frequency and the phase lag between deformation and load. The complex modulus, however, can yield valuable information on fundamental material properties such as stiffness and damping provided that it is properly interpreted. From the theoretical point of view, neither the dynamic modulus nor the complex modulus is suitable for use in elastic multilayer computer programs used in pavement analysis because they do not represent elastic parameters. The complex modulus can be used in viscoelastic pavement models in which the time-dependent response is considered.

RESILIENT MODULUS

Pavement materials are subjected to repetitive loading that tends to "shake down" their response through strain hardening. Thus, after several repetitions of loading, subsequent deformations become predominantly recoverable and, often, substantially linear. The resilient modulus is the ratio of repeated stress to corresponding recoverable or resilient strain during such loading; that is, it is the elastic stiffness of the material after many load repetitions have been applied. Therefore the resilient modulus of asphalt mixtures is more appropriate for use in multilayer elastic programs than are other moduli. Also, the moduli predicted from the dynamic nondestructive testing of pavements are more representative of the in situ resilient moduli of the materials. The resilient modulus can be determined in the laboratory using the axial, triaxial, or diametral method.

Axial or Triaxial Method

The axial or triaxial resilient modulus test on asphaltic materials is performed by applying a pulsating axial load to a cylindrical specimen and recording the recoverable axial deformation while keeping the confining pressure zero or constant (8). The resilient modulus is the ratio of the repeated axial stress to the recoverable axial strain after many load repetitions. Figure 4 shows the typical relation between stress and strain in an asphalt concrete specimen when repeated load is applied. The figure shows that the stress-strain relation is essentially linear after several load applications. The resilient

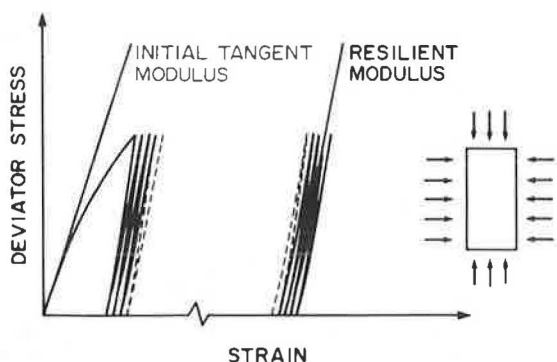


FIGURE 4 Typical stress-strain response during triaxial resilient modulus test.

modulus is, therefore, the slope of the stress-strain curve after many load repetitions are applied. This indicates that the resilient modulus is the “current” modulus of the material, given the repetitive nature of the traffic load. The resilient modulus of asphalt concrete can be used in the elastic layer analysis of pavements with a large degree of accuracy. A typical relation among load, deformation, and time is shown in Figure 5. Note that two resilient moduli can be obtained, instantaneous and total, depending on which response is considered. The instantaneous resilient modulus, however, is more consistent with elastic theory than is the total resilient modulus. Currently, there is no standard test procedure for the axial or triaxial test method. A standard test procedure is, however, available for determining the resilient modulus of subgrade soils (AASHTO T-274).

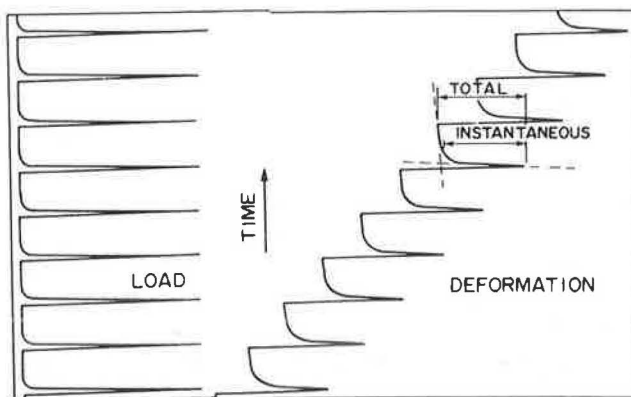


FIGURE 5 Typical plot of load and deformation versus time during resilient modulus test.

Diametral Method

In the diametral resilient modulus test (ASTM D 4123), a pulsating load is applied along the vertical diameter of a Marshall-sized specimen of asphalt concrete, and the horizontal or the vertical deformation, or both, are recorded (Figure 6). The stress distribution in the specimen when the load is applied is shown in Figure 7 assuming plane stress condition (9). It should be noted that the plane stress condition is valid only when the thickness of the specimen is quite small in comparison with its diameter (e.g., disk). Therefore the validity of this assumption is questionable for a Marshall-sized specimen.

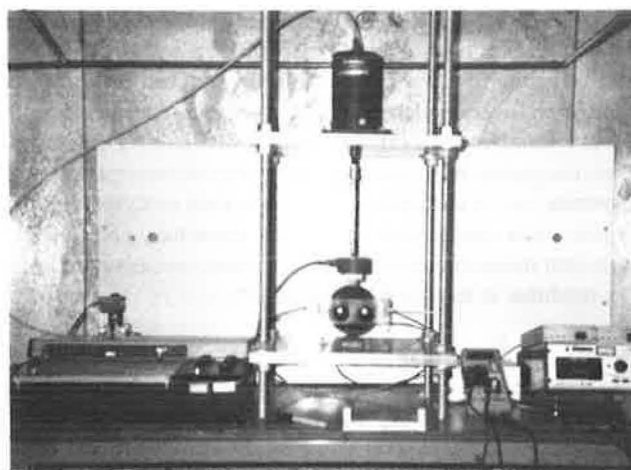


FIGURE 6 Diametral resilient modulus apparatus.

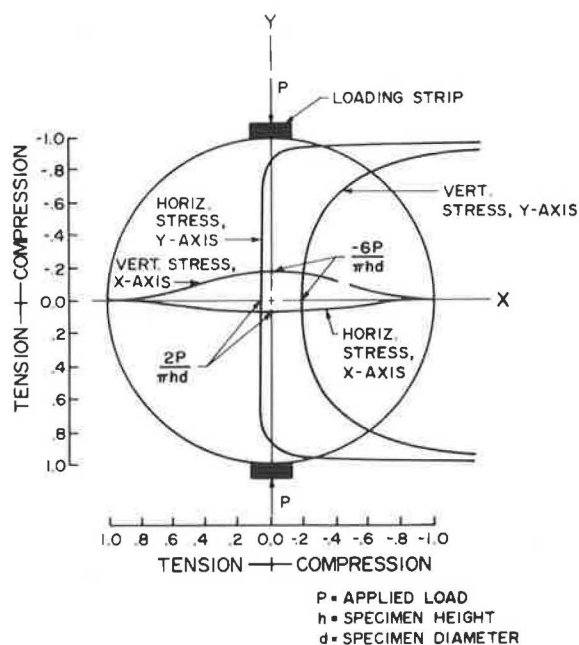


FIGURE 7 Stress distribution along the principal axes of specimen during diametral resilient modulus test.

The relation among load, vertical deformation, horizontal deformation, and time is similar to that of the axial resilient modulus test (Figure 5). Assuming linear elastic material response, the resilient modulus can be computed as reported in the ASTM D 4123 procedure. As is the case with the triaxial method, both instantaneous and total moduli can be determined.

Comparison of the triaxial resilient modulus method with the diametral method indicates that the triaxial method is more representative of field conditions because of the triaxial nature of the load. This is particularly important at high temperatures for two reasons. The first reason is that the asphalt gets soft at high temperatures and the modulus would be largely dependent on the amount of confining pressure. Thus, if the correct confining pressure is used, a better approximation of the in situ

modulus of the material is obtained. The second reason is that a large amount of tensile stress is developed in the specimen as shown in Figure 7. Consequently, when the asphalt binder gets soft at high temperatures, artificially low moduli are obtained that do not represent the true stress-strain relation of the asphalt-aggregate mixture in the field; instead, they represent responses that are largely affected by the tensile strength of the binder.

SHELL NOMOGRAPH MODULUS

The modulus of an asphaltic mix obtained by the Shell Oil Company (Van der Poel) nomograph (10) is based on more than 20 years of laboratory work and correlation analysis. The method uses a nomographic solution to obtain the modulus of the asphalt and equations to convert this value to the modulus or stiffness of the asphalt mix. It is assumed that the asphalt mix is a viscoelastic material, properties of which are dependent on the duration (or frequency), of loading and on the temperature at which the load is applied. Thus, if the load time (or frequency), temperature, properties of asphalt cement, and mix ingredient are known, the stiffness modulus can be determined from the nomograph.

During the original development of the Shell nomograph the "two-point" bending apparatus was used to determine the modulus of asphalt concrete (Figure 8). In this test a trapezoidal specimen fixed in a cantilever form is subjected to sinusoidal loads at its free end. A continuous plot of load and deformation is obtained, and the stiffness modulus is defined as the ratio of the amplitudes of stress to strain. Therefore the stiffness modulus obtained from the Shell (Van der Poel) nomograph

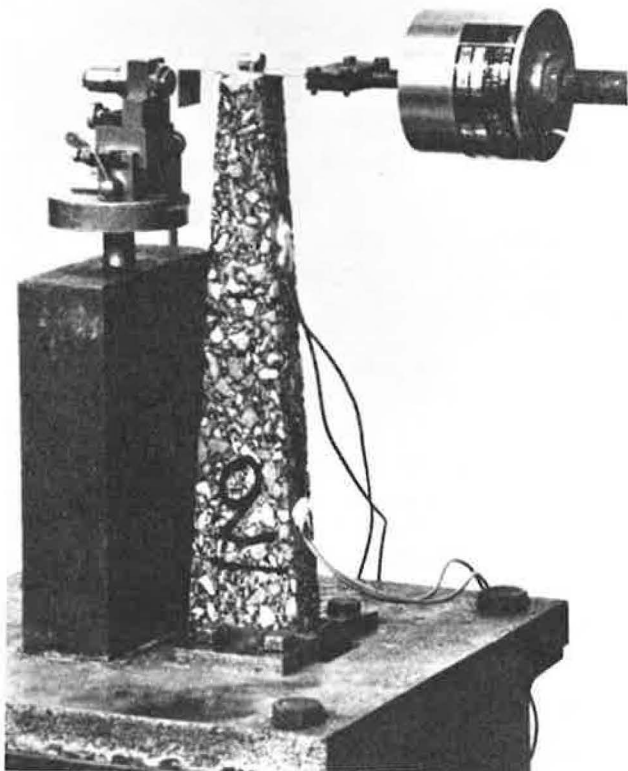


FIGURE 8 Two-point bending apparatus used in Shell method (10).

is a prediction of the dynamic modulus discussed previously, with the exception that a trapezoidal specimen was used instead of a cylindrical specimen.

The Van der Poel nomograph concept was further extended by Bonnaure et al. (11) to predict the phase lag in addition to the stiffness modulus of the asphalt mix. By using the stiffness modulus and the phase lag, the complex modulus can be obtained as discussed previously.

SUMMARY AND CONCLUSIONS

The moduli commonly used to characterize asphaltic mixtures have been discussed in terms of the basic theory of strength of materials. A rational understanding of stiffness parameters—Young's, shear, bulk, complex, dynamic, double-punch, resilient, and Shell nomograph moduli—has been presented. The assumptions used to define these moduli, such as material linearity, elasticity, and viscoelasticity, have been specified.

The appropriate modulus to be used is dependent on assumptions of material response, method of analysis, and required accuracy. In some cases, asphaltic materials can be assumed to be linear elastic especially in multilayer elastic analyses in which repeated loads are applied to pavements. In such cases the triaxial or diametral resilient modulus can be used to characterize the material. If more accuracy is needed, the non-linearity of the material (or the change in the modulus with change in the state of stress) can be considered. In such cases, the triaxial resilient modulus is more appropriate to use than is the diametral resilient modulus. Also, the triaxial modulus is useful at high temperatures at which the viscosity of the binder gets small and the effect of confining pressure becomes significant. In addition, the moduli predicted from the dynamic non-destructive testing of pavements are more representative of the in situ resilient moduli of the materials.

The dynamic modulus is a frequency-dependent parameter and ignores the phase lag between load and deformation. However, the complex modulus considers both stiffness and phase lag. From the theoretical point of view, neither the dynamic modulus nor the complex modulus is suitable for use in elastic multilayer computer programs because of the inconsistency of the assumptions. The double-punch modulus or the modulus predicted from the Shell nomograph is conceptually similar to the dynamic modulus except that a different load configuration or specimen shape is used.

In conclusion, for the purpose of comparing different asphalt mixtures, any modulus (dynamic, resilient, etc.) can be used as long as the same modulus is used for all mixtures. If the modulus is to be used in a specific empirical formula, the test procedure used during the original development of the formula should be followed. On the other hand, if the modulus is to be used in a specific empirical formula, the test procedure used during the original development of the formula should be followed. On the other hand, if the modulus is intended to be used in a theoretical or mechanistically based analysis, any test procedure can be followed as long as an interpretation of the test results that is consistent with the assumptions of the analysis is used. When proper material characterization is used, reliable performance models, which are important for both pavement design and pavement management, can be developed.

Further research is needed to provide typical laboratory results of different moduli of asphalt mixtures. It would also be useful if these different moduli were input into the same multi-layer computer programs and the relative outcomes (stresses, strains, deflections, etc.) were compared.

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