Procedures for Estimation of Asphalt Concrete Pavement Moduli at In Situ Temperatures

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Methods to supplement conventional elastic layer analysis of nondestructive test (NDT) measurements are needed to improve the ability to evaluate layer moduli. In particular, the determination of asphalt concrete moduli (E_1) for thin pavements often results in substantial errors in the values of E_1 and E_2 using iteration techniques in computer programs (e.g., ELSYM-5, ISSEM-4). The development and predictive reliability of two methods of E_1 determinations are presented for the purpose of improving the analysis techniques used in pavement evaluation studies. The methods are classified as direct and indirect even though both methods are based on E_1-values from dynamic indirect tension testing of asphalt concrete specimens (cores or compacted samples). The direct method requires the development of an E_1-temperature relationship using E_1-values from the indirect tension test, which is conducted at different temperatures. The indirect method is based on a previously developed relationship between E_1 and constant power viscosity (η_j) of the asphalt as obtained from Schweyer constant stress rheometer tests. Cores or cut samples from the pavement are separated into individual layers and the asphalt is recovered using reflux and Abson methods. Asphalt viscosity (η_j) determinations from tests at different temperatures are used in a regression analysis to develop an η_j versus temperature (°K) relationship. Pavement temperature recorded at the time of NDT measurements is used to determine a corresponding η_j from the relationship. E_1 is then predicted from the developed equations using this η_j-value. The reliability of the E_1 predictions is appraised by comparing layer moduli from BISAR simulation of Dynaflect-measured deflection basins and ISSEM-4 predictions of falling weight deflectometer deflection basins. Comments are made on the effects of air void content and mix characteristics.

The analysis of nondestructive test (NDT) measurements for evaluation of the structural characteristics of flexible pavement systems is often complicated by temperature differences, variations in underlying support caused by moisture content changes, the number and relative stiffness of layers being considered in the analysis, and the approach followed in determining layer moduli. Iteration of layer moduli in elastic layer computer programs can yield erroneous results even though the predicted deflection basin is essentially the same as that measured by NDT equipment (e.g., Dynaflect, Road Rater, falling weight deflectometer). Therefore, it is desirable to develop procedures that provide layer moduli independent of other pavement layers. These moduli can be used in multilayer analyses to minimize the number of variables in the iteration. For example, the fifth Dynaflect sensor deflection response can be used for estimation of subgrade or foundation modulus.

Two methods for the determination of asphalt concrete modulus (E_1) are presented. The direct method involved the dynamic indirect tension testing of cores or laboratory-compacted specimens using a bonded strain gauge for horizontal strain measurements. The results of tests at different temperatures provided modulus values from which a modulus-temperature relationship was developed for prediction of modulus at the pavement temperature or temperatures encountered during nondestructive testing.

A comprehensive laboratory study was performed using the direct method and constant power viscosity (η_j) tests on asphalt recovered from the test specimens. The resilient modulus and viscosity data obtained from these tests were used to develop relationships between E_1 and η_j. This provided the basis for development of the indirect method for estimation of E_1.

The indirect method requires: *(a)* the recovery of asphalt from each layer of asphalt concrete; *(b)* viscosity testing of the recovered asphalt at different test temperatures; *(c)* regression analysis of the data to establish an η_j versus temperature relationship; and *(d)* prediction of E_1 using the η_j-values computed at temperatures corresponding to those of the pavement during nondestructive pavement evaluation tests.

DEVELOPMENT OF RESILIENT MODULUS TESTING PROCEDURES

The resilient modulus of asphalt concrete mixtures can be determined using compression, flexural, or different indirect tension test methods. Difficulty is encountered with both the interpretation of test data and the reliability of test procedures for providing realistic values of moduli for use in elastic layered stress analysis computer programs.

The compression test is usually performed in an unconfined or triaxial mode using test specimens that have a length-to-diameter ratio of 2. This requires special emphasis on the compaction equipment and procedures used to produce the test specimen. Conventional test specimens are 4 in. in diameter and only 2½ in. thick. It appears to be more rational to evaluate tensile properties because both elastic and inelastic behavior affect elastic response and contribute to cracking (fracture) of pavements subjected to tensile stresses.

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The flexural test has similar drawbacks. Furthermore, the nonuniform stressing condition throughout the depth of the specimen makes it more susceptible to variation in test results. Even though the viscosity of the binder is the same at the test temperature, test specimens prepared with a highly shear susceptible binder will not yield the same response or resilient moduli as specimens that contain a low shear susceptible asphalt. This condition has also been observed in dynamic indirect tensile tests using the measured diametral deformation for resilient modulus evaluation. In these tests highly shear susceptible asphalts respond more elastically with fewer delayed elastic effects *(1)*. This produces noticeably higher resilient modulus values for mixtures that contain highly shear susceptible asphalts (e.g., steep roofing) than are obtained with conventional paving asphalt. This difference in response and the variation in temperature susceptibility of asphalts suggests that it is not possible to adjust NDT measurements for temperature without performing tests either on the mix or on the asphalt binder.

Experience with the dynamic indirect tension test with both diametral deformation measurements and bonded strain gauges has indicated that more precise and consistent strain measurements are obtained with bonded strain gauges. At low temperatures, where the specimens behave as brittle elastic materials, both methods should yield the same results provided the precision of the measurement methods is about equal. However, at warmer temperatures the viscosity and elastic behavior of the asphalt binder interact with loading time, rest time, and specimen geometry to inhibit the accurate determination of resilient moduli using the diametral equations that are based on elastic response:

$$E_R = \frac{\sigma_{xx}(1 + 3\upsilon)}{\varepsilon_{xx}} \tag{1}$$

where

E_R = resilient modulus (psi),
σ_{xx} = computed tensile stress (psi),
ε_{xx} = computed strain from diametral measurements, and
υ = Poisson's ratio.

DIRECT METHOD FOR DETERMINATION OF E_1

The test procedure that has evolved from prior experimentation requires the use of an indirect tension testing device equipped with 0.5-in.-wide loading strips that are curved to fit 4.0-in.-diameter test specimens. The device was installed in an environmental chamber set under the crosshead of an MTS closed-loop testing machine. Temperature control was achieved using a dummy specimen with thermistors or thermocouples installed on its surface and interior to provide direct temperature measurements for manual adjustment of the servo-valve for the liquid nitrogen cooling medium. Instrumented test specimens are placed in the chamber along with the dummy specimen and cooled to the specified temperature or temperatures. After the specimen was preconditioned, 20 cycles of loading are usually applied at each of five or more stress levels. A 0.1-sec haversine loading followed by a 0.4-sec rest period is conventionally used in the resilient modulus test.

Test specimens are either compacted in the laboratory to a thickness of 2.50 in., or 4.0-in.-diameter cores are cut from the pavement and trimmed with a masonry saw to a thickness of from 2 to 3 in. It is essential that cores be obtained perpendicular to the pavement so that asphalt concrete layers are normal to the core surface for easy separation by sawing. Also, care must be taken to obtain a uniform cut surface on the core. Surface irregularities will result in excessive stress concentrations when the specimen is loaded between the curved loading strips. One major problem is how to accommodate multiple thin lifts without inducing excessive testing error. Combined lifts of the same asphalt concrete can be cut to 2 or more in. in thickness for testing. Specimens as thin as 1.5 in. can be used if they are within the paving layer. In all cases in which sample size is inadequate there is a greater chance for test discrepancies to occur. The other procedure is to use asphalt viscosity values for asphalt extracted from each layer for computation of moduli using the indirect method.

The preparation of cores for installation of a 0.5-in.-long strain gauge requires the removal of dust from a cut surface before gauge installation. In the case of laboratory-compacted specimens, precooled specimens should be sandblasted or sandpapered on their flat face until clean aggregate is exposed. Strain gauges are epoxied horizontally along or parallel to the *x-x* axis (within ± 0.3 in.) and the gauge is centered about the vertical loading axis (*y-y*). The lead wires from strain gauges are connected to a strain bridge balance, and the output is connected to a strip chart or *x-y* recorder with a time base for recording the dynamic strain response. A quarter bridge configuration can be used with good results or, if the effect of temperature variation is questioned, a half bridge setup using an unloaded instrumented specimen for temperature compensation may be employed.

Testing may start at 25°C (77°F) provided the asphalt binder is sufficiently hard as encountered with pavement cores from old pavements or laboratory specimens prepared with at least an AC-20 or harder grade asphalt cement. If the specimen has insufficient compacted density or too soft a binder, or both, the stiffness of the strain gauge will be excessive and prevent development of realistic strains. When the stiffness of the asphalt is less than the gauge stiffness, the gauge prevents the full development of strains in its vicinity. This is comparable to strain gauge slippage due to inadequate curing of the epoxy on an elastic material (e.g., steel).

The first step before dynamic testing is to precondition the specimen. This is accomplished by applying a constant low stress for sufficient time to accumulate about 150-μin. of creep strain and then allowing time for strain recovery before the dynamic tests are begun. It is best to precondition and test at warm temperatures before testing at low temperatures. Preconditioning at low temperatures to this strain level could result in damage to the specimen and initiation of fracture.

Stress levels must be selected to prevent excessive creep accumulation or damage to the test specimen. For example, stresses of 2, 4, 6, 8, and 10 psi may be selected for 25°C tests and stresses of as much as 200 psi for tests conducted at 0°C or -5°C. Generally speaking, stress levels should not exceed 50 percent of the failure stress from standard indirect tension tests (at 2 in./min).

Resilient moduli are computed for each stress level and each test temperature using the total resilient strain and the computed stress:

$$\sigma_x = \frac{2P}{\pi l d} \tag{2}$$

$$E_R = \frac{\sigma_x}{\varepsilon_x} \tag{3}$$

where

σ_x = indirect tensile stress (psi),
P = applied load (lb),
l = thickness of specimen (in.),
d = diameter of specimen (in.),
ε_x = measured horizontal strain, and
E_R = resilient modulus (psi).

Specimens properly preconditioned and tested without overstressing will yield almost identical E_R-values for the different stress levels at a given temperature. Usually the mean of four or more E_R-values is considered representative of the resilient modulus at a given test temperature.

Test temperatures of -5°C, +5°C, 15°C, 25°C, and sometimes higher are often used for resilient modulus testing to represent Florida's lower temperature range. The test results can be plotted on log-log graph paper, and regression analyses can be performed for prediction of E_R within and above the test temperature range as shown in Figure 1. Obviously, for colder climates additional tests may be derived at lower temperatures to aid in low-temperature pavement response evaluation or predictions using elastic layer computer programs.

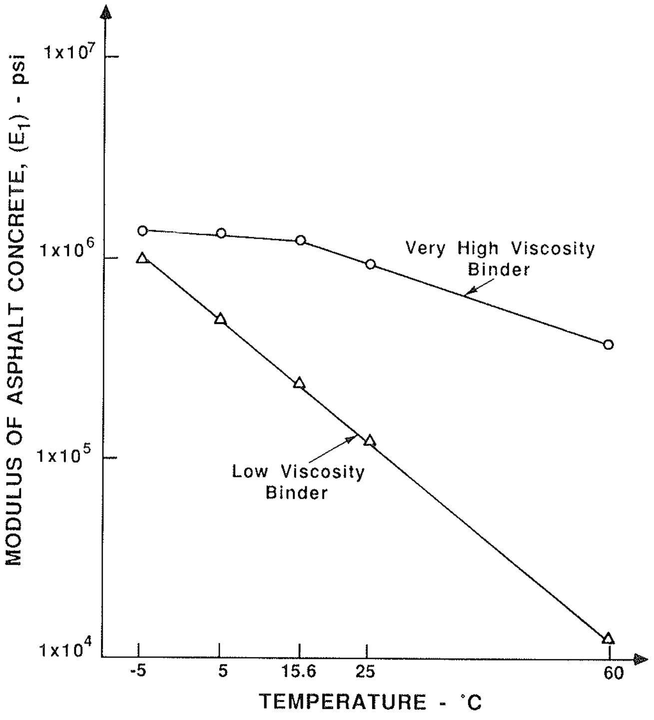

FIGURE 1 **E_1-temperature relationships.**

INDIRECT METHOD FOR DETERMINATION OF E_1

In many instances asphalt concrete pavements have multiple thin lifts or inadequate total thickness for resilient modulus testing using the direct method. Consequently, relationships previously developed from a laboratory test program can be used to predict E_1 for dense-graded mixtures using the viscosity of the binder *(2)*. The relationship was originally developed using a variety of asphalts to prepare test specimens for the previously described dynamic indirect tension tests. After testing, the asphalts were recovered and tested at different temperatures using the Schweyer constant stress rheometer *(3)*. Relationships between E_R and constant power viscosity (η_j) were developed and subsequently used for the prediction of E_1 when the viscosity of asphalts recovered from pavements was known.

The indirect method requires that cut or cored samples be obtained from the pavement section being evaluated. These samples are separated according to each layer or type of asphalt concrete, then heated and broken down for extraction using Method B (reflux) of ASTM D 2172, "Quantitative Extraction of Bitumen from Bituminous Paving Mixtures." The asphalt is recovered using the Abson method (ASTM D 1856). The recovered asphalt is poured into sample tubes with attached capillary tube for viscosity determination at different shear stresses and test temperatures. Background and basic information on the use of the Schweyer constant stress rheometer are available elsewhere *(3–5)*. Details of the physical characteristics, operation, and computational methods of the Schweyer constant stress rheometer are presented in Tia and Ruth *(6)*. Also, Roque et al. *(7)* provide additional information on the relationships between mix properties and asphalt viscosity.

One of the most important aspects of the determination of asphalt viscosity is the asphalt's shear susceptibility at each test temperature. A slight error in the shear susceptibility (slope of Log shear stress versus Log shear rate relationship) may result in errors in viscosity values. The use of constant shear rate (e.g., 1.0- or 0.05-sec^{-1}) viscosity calculations for low-temperature tests will almost always produce problems in developing a good viscosity-temperature relationship. The constant power approach (100 watts/m^3) gives a viscosity (η_j) that has shear stresses and shear rates close to or within the range of those measured. Consequently, errors in shear susceptibility are minimized by using the constant power viscosity.

Basic viscosity calculations using the Schweyer rheometer include

$$\eta_{1.0} = \frac{\tau' \times G}{(\dot{\gamma}' \times R)^c} \tag{4}$$

where

$\eta_{1.0}$ = apparent viscosity at a shear rate of 1.0 sec^{-1} (Pa-sec),
τ' = uncorrected shear stress (Pa),
$\dot{\gamma}'$ = uncorrected shear rate (sec),
G = geometric correction factor,
R = Rabinowich correction = $0.75 - \frac{0.25}{C}$, and
C = shear susceptibility factor (complex flow).

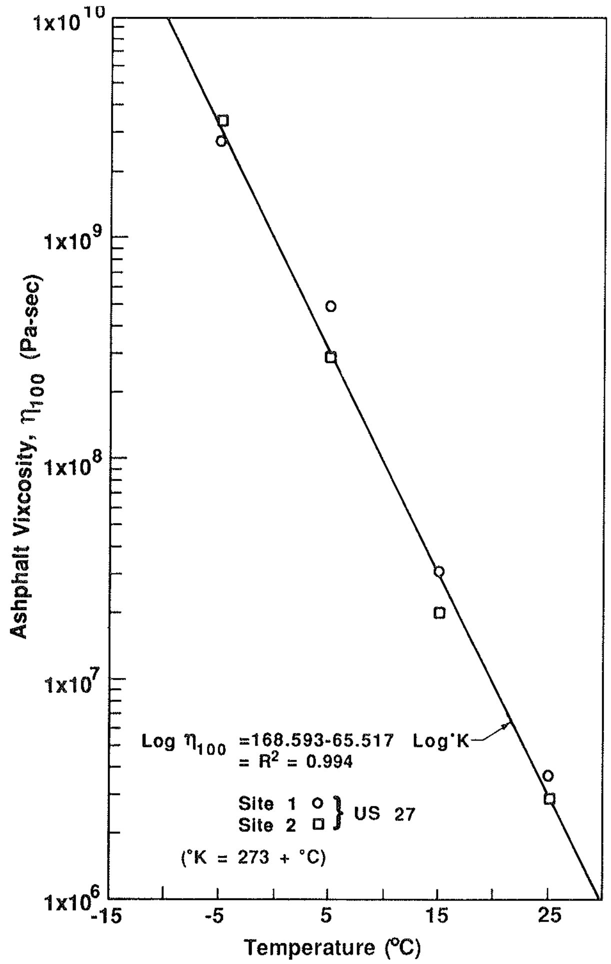

FIGURE 2 Low-temperature asphalt rheology.

To convert $\eta_{1.0}$ to a constant power corresponding to $j = \tau_j \dot{\gamma}_j = 100$ watts/m^3,

$$\eta_j = \eta_{100} = \eta_{1.0}\left(\frac{100}{\eta_{1.0}}\right) \exp\left(c_{-1}/c_{+1}\right) \quad (5)$$

The viscosity-temperature relationship may be established by regression analyses of test results and plotted as shown in Figure 2. Usually four to six temperature levels are used to establish the viscosity-temperature relationships. Often it is possible to incorporate the absolute viscosity at 60°C (140°F) in the regression analysis provided the trend is not excessively altered. In this case two sample sites were selected from the pavement of US-27, which had been evaluated by Dynaflect. If the Dynaflect tests had been performed at a temperature of 10°C (50°F), the viscosity (η_{100}) would be determined using the regression equation

$$\text{Log } \eta_{100} = 168.593 - 65.517 \text{ Log } (°\text{K}) \quad (6)$$

where

°K = 273 + °C,
n = 8, and
R^2 = 0.994,

which would yield a constant power viscosity of 9.11 × 10^7 Pa-sec.

The resilient modulus of the asphalt concrete pavement layer (E_1) can then be computed using one of two equations selected on the basis of viscosity *(2)*:

For $\eta_{100} \leq 9.19 \times 10^8$ Pa-sec,

$$\text{Log } E_1 = 7.18659 + 0.30677 \text{ Log } (\eta_{100}) \quad (7)$$

For $\eta_{100} > 9.19 \times 10^8$ Pa-sec,

$$\text{Log } E_1 = 9.51354 + 0.04716 \text{ Log } (\eta_{100}) \quad (8)$$

These equations were originally developed using data derived from mixtures prepared with a Pennsylvania aggregate blend with five different asphalts and a Florida aggregate blend using nine different asphalts that were tested at five stress levels and four different temperatures *(2)*. In this case Equation 7 is used to compute E_1. This gives a value for E_1 equal to 4.25 × 10^9 Pa-sec or 616,000 psi. Figure 3 shows a comparison of

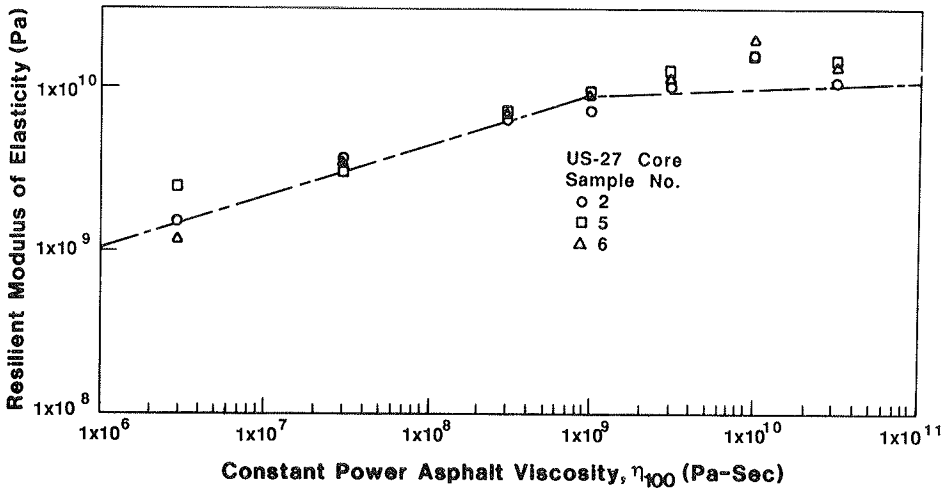

FIGURE 3 Resilient modulus–asphalt viscosity relationship and comparison.

relationships of Equations 7 and 8 with E_1-values obtained by the direct method of testing.

Care should be exercised in the use of Equation 8 because this is an approximation of the extension of Equation 7 to simulate a curved relation that attains maximum E_1-values in the range of from 2×10^{10} to 5×10^{10} Pa. Therefore, predicted E_1-values in excess of 5×10^{10} should be questioned or considered in error. The majority of test results indicates that maximum E_1-values are generally less than 3×10^{10} Pa.

The preceding indirect method for estimation of E_1 has worked exceedingly well for dense-graded mixtures with air void contents within the 3 to 7 percent range. Higher air void contents result in a reduction in measured E_1-values. Southgate *(8)* developed a relationship between modulus ratio and air void content. Dynamic flexural tests conducted by Ruth and Maxfield *(9)* provided results almost identical to Southgate's relationship. These relationships, shown in Figure 4, indicate an 11.0 percent reduction in E_1 for each 1.0 percent increase in air void content over 4.0 percent but not in excess of 9.0 percent. At low temperatures (high asphalt viscosity) the effect is considerably less because the asphalt binder properties influence E_1 more than compacted density or air void content. The reverse is true at extremely warm pavement temperatures.

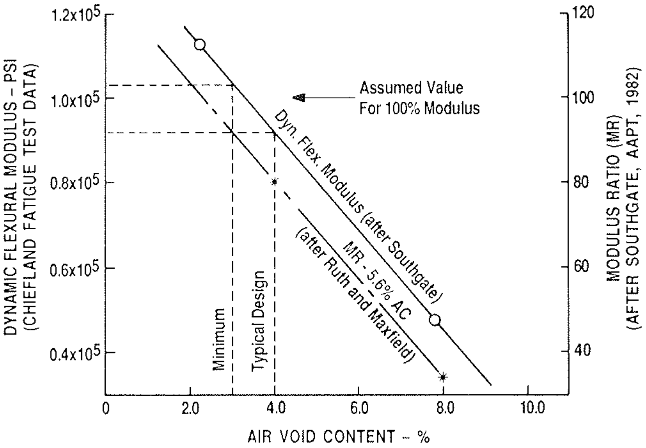

FIGURE 4 Effect of air void content on modulus.

RELIABILITY OF PREDICTED E_1-VALUES

The reliability of the indirect method of estimating E_1 is quite good according to comparisons of predicted and measured values determined by the dynamic indirect tension test using bonded strain gauges. The most prevalent predictive error occurs at higher-than-normal air void contents (> 7.0 percent) when the viscosity of the binder is low.

Another indicator of reliability is if predicted E_1-values can be used with E_2-, E_3-, and E_4-values as input in an elastic multilayer computer program (e.g., BISAR) to predict Dynaflect deflection basins without further adjustment of E_1. Of nine test road sites given in Table 1, only SR 26B required a significant change in E_1 to achieve simulation of pavement response as measured by Dynaflect. Also, the results of ISSEM-4 *(10)* predictions of E_1 using falling weight deflectometer deflection basins are given in Table 1. The predicted E_1-values were used as seed moduli in the ISSEM-4 analysis.

CONCLUSIONS

The need for methods to evaluate the moduli of pavement layers without excessive extrapolation error is most apparent when NDT data and iteration methods are used to solve for the moduli of three- or four-layer systems. This is particularly true when the asphalt concrete modulus (E_1), which is affected by temperature, layer thickness (t_1), and the stiffness of underlying pavement layers, is considered. Two methods of providing a more direct approach for the estimation of E_1 have been presented:

TABLE 1 COMPARISON OF PREDICTED AND TUNED ASPHALT CONCRETE MODULI

Test Road	Thickness of AC (in.)	Pavement Temp. °F	Asphalt Concrete Modulus (E_1), psi		
			Predicted[(a)]	Tuned w/ BISAR[(b)]	ISSEM-4[(c)]
SR 24	2.5	55	338,260	338,260	338,000
SR 26A	8.0	81	171,250	171,500	174,000
SR 26B	8.0	59	406,493	360,000	360,000
SR 26C	6.5	82	171,250	171,500	171,000
US 301	4.0	69	256,640	250,000	250,000
US 441	3.0	79	289,580	290,000	290,000
I-10 A	8.0	104	60,776	65,000	-
I-10 B	7.0	88	113,182	113,000	113,000
I-10 C	5.5	106	66,888	67,000	67,400

(a) Predicted from recovered asphalt viscosity-temperature relationship and E_1 prediction equations.

(b) Layer moduli obtained when BISAR predicted deflection basins match those measured by Dynaflect.

(c) Layer moduli obtained from ISSEM-4 using initial estimates of layer moduli (seed moduli) for the four layer system as input into the program. ISSEM-4 iterates layer moduli to achieve a close match of the deflection basin measured by the Falling Weight Deflectometer.

1. The first method involves the direct measurement of horizontal strain in the dynamic indirect tension test and computation of E_1 using only the computed stress (σ_{xx}), measured total resilient strain (ε_x), and Equation 3. This method is only limited by specimen size and a sufficiently high binder viscosity. Otherwise, reproducible test results and reliable E_1-values are obtained for most mixtures.
2. The second method is considered an indirect estimate of E_1 because recovered asphalt viscosity has been related to E_1-values obtained from direct measurement (first method). The major advantage to the use of the indirect method is its adaptability to thin asphalt concrete pavements or thin lifts where direct measurement on samples is not feasible.

The prediction accuracy of both methods is considered to be quite good on the basis of results of BISAR simulation of Dynaflect response and ISSEM-4 predictions of falling weight deflectometer measurements using these E_1-values.

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