Evaluation of Testing Procedure for Dynamic Modulus of Asphalt Concrete

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Abstract— The strength of asphalt concrete can be measured in terms of its dynamic modulus that is appropriate for structures subjected to earthquake and impact loading caused by both the moving vehicles and aircraft's. Presently a large number of testing procedures are available for calculating the dynamic modulus of asphalt concrete. All these procedures are evaluated in this paper.

Index Terms— Strength of asphalt concrete, Dynamic Modulus, earthquake and impact loading, Laboratory tests, Field tests, Indirect tests

1 Introduction

Flexible pavements including primarily those that have an asphalt concrete surface are an essential part of construction work and play an important role in our daily life.
These pavements are designed by using some appropriate design procedures. Among them one is empirical, while the other is based on elastic theory. In both these procedures the dynamic modulus which represents the concrete strength is utilized for initial design and assessing the structural adequacy and estimating rehabilitation needs of existing structures subjected to small strain loading condition. A large number of testing procedures are available to measure the dynamic modulus of asphalt concrete. All these procedures are presented in this paper.

2 Testing Procedure

Many testing methods are available for evaluation of asphalt concrete.

2.1 Lab Testing

Asphalt concrete samples are tested with some equipment in this method. A large number of such equipment is available. The following section describes the some of these equipment, which are used to calculate the dynamic modulus value of asphalt concrete samples.

2.1.1 Resonant Column Test

The asphalt concrete samples used for testing had an average height of 3 inches and an average diameter of 2 inches. This apparatus was also used to note the effect of temperature on the properties of concrete i.e there was an arrangement to change the temperature the sample remained in the chamber at the chosen temperature for 24 hours before testing.
The asphalt concrete sample was excited to vibrate in this procedure, in order to obtain the resonant frequency. Once this frequency was known, the modulus value could be calculated [4].

2.1.2 Diametral Modulus

The modulus of asphalt treated mixtures can be determined by means of a diametral resilient modulus (M_R) device. In this procedure, a pulsating load is applied along the vertical diameter of asphalt samples similar in size to those used for the widely known Marshall and Hveem tests. The dynamic load, in turn, results in dynamic deformations across the horizontal diametral plane. These deformations are recorded by transducers mounted on each side of the horizontal sample axis. Knowing the intensity of the dynamic load and deformations, the modulus value can be calculated using the elastic theory.
The test has many advantages, the most obvious being the simplicity of the test procedure [3]. The theoretical distribution of the stress for a concentrated load is given by the following equations.

Horizontal diametral

$$\sigma_x = 2p/\pi td\{(d^2 - 4x^2)/(d^2 + 4x^2)\}^2$$

$$\sigma_y = 2p/\pi td[\{4d^2/(d^2 + 4x^2)\} - 1]$$

$$\tau_{xy} = 0$$

Where p is the total applied load (lb).; t is the sample thickness (in); d is the sample diameter (in), and x and y are the co-ordinate value from the centre of the sample assuming that plane stress condition are applicable ($\sigma_Z = 0$), the resultant strain ϵx , along the horizontal diametral is given by

$$\epsilon_x = 1/E\{ \sigma_x - \mu\sigma_y \}$$

Substituting in the above equation yields

$$\epsilon_x = 2p/E\pi td\{(d^4(1 + 5\mu) - 8x^2d^2(1 - 3\mu) + 16x^4(1 + \mu))/(d^2 + 4x^2)^2\}$$

The deformation across the horizontal diameter ($Y = 0$) may be found by integrating above equation between $x = -d/2$ and $x = d/2$. This result in horizontal deformation being equal to

$$\delta^h = p/te\{4/\pi + \mu - 1\}$$

Thus, for applied dynamic load of p in which resulting horizontal dynamic deformation is measured the modulus or M_R value is

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$$M_R = \{p(\mu + 0.2734)\}/t$$

A commonly used value of poisson's ratio (μ) for asphaltic material is 0.35. Deviations from this value result in non-excessive errors in the calculated M_R.

2.1.3 Dynamic Modulus

The mechanical properties of visco-elastic materials are dependent on the frequency of loading and the temperature at which the load is applied. In a two point bending machine test, sinusoidal stresses $\sigma_o \, sin\omega t$ are applied [3]. The resulting strain i.e $\epsilon_o \, sin\,(\omega t - \phi)$ is also sinusoidal. Both recorded signals have the same frequency but there is a phase lag between the stress and strain. The stiffness modulus S_m is defined as the ratio of the amplitude of the stress to the strain

$$S_m = \sigma_o / \epsilon_o$$

The phase lag ϕ is called the loss (or phase) angle. The value of ϕ indicates the elastic or visco-elastic character of the material. The phase angle for an elastic material and equal to 90 degrees for a pure viscous material. The complex modulus of a visco –elastic body is the complex number E whose modulus is S:

$$E = Se^{i\phi} = s(cos\phi + isin\phi)$$

The concept of a complex modulus has been introduced to generalize the laws of mechanics normally applied to both elastic and non-elastic bodies. The same formula can be applied to elastic or visco-elastic materials as well, but by using complex numbers for the latter. The real and imaginary parts of the complex modulus, s $cos\phi$ and $s\,sin\phi$, are often called the conservation modulus and loss modulus, respectively.

Procedures used for determining the dynamic modulus (also called complex modulus) of asphalt concrete are based on those developed by Papazian [3]. The test procedures and equipment used to determine the dynamic modulus E and a phase lag ϕ of asphalt concrete compression are described by Kallas and Riley [3]. For dynamic modulus determinations, 4-in. diameter, 8-in. high, unconfined specimens are subjected to sinusoidal axial stresses and the resultant axial strain are measured with a pair wire strain gauges cemented to the sample at mid-height. A typical recorded trace of the axial sinusoidal loadings (zero to maximum compression load to zero load again) and a resultant axial sinusoidal strains are obtained during a dynamic compression modulus test. E and ϕ are calculated from measured and recoverable strains.

2.1.4 Flexural Stiffness

Another common test is used in a repeated load flexure device with beam samples (13). In this test, a beam sample is subjected to repeated flexure loads of the haversine wave form having a load duration of 0.1 seconds and rest period of 0.4 seconds. The stiffness at any given test temperature is calculated from

$$E_s = \{Pa(3L^2 - 4a^2)\}/(48\, I\, \Delta)$$

Where E_s is the flexural stiffness (psi); P is the dynamic load applied to deflect the beam (lb) a is equal to ½$(L+4)$ $(in.)$; L is the span length $(in.)$; I is the sample moment of inertia (in^4), and Δ is the measured dynamic beam deflection at the center point $(in.)$.

2.1.5 Creep Compliance (Visco Elastic Property)

Visco-elastic properties are utilized by VESYS IIM in its computer program [5]. Normally, creep compliance is determined by applying a constant axial load to a sample and measuring the time –dependent deformation that occurs. Creep compliance is then calculated by dividing the strain by the applied tress as follows:

$$Jt = \epsilon_t / \sigma$$

Where ϵ_t is the strain at time t; at any temperature T; σ is the applied stress, psi.

2.1.6 Ultrasonic Pulse Velocity Test

The dynamic modulus of concrete can be obtained by the pulse velocity technique [7]. In this method, an electrical timing unit measures the time taken for a pulse to travel through the concrete with an accuracy of $\pm$ 0.1μ sec. Once this time is known, the dynamic modulus can be calculated by:

$$E = (Vc^2\gamma)/g$$

Where

E = Dynamic modulus of elasticity (psf)

Vc = Longitudinal wave velocity (ft/sec)

g = Acceleration due to gravity (ft/sec^2)

γ = Unit weight of the sample (lb/ft^3)

2.1.7 Impulse Load Test with Hammer

This method is used to determine the dynamic modulus of concrete [7], and is becoming very useful in locating flaws in concrete members also [1]. The testing components consist of a hammer or impactor, an accelerometer, and a Fast Fourier transfer (FFT) signal analyzer [2].

In this procedure an impulse load is produced by striking the surface of a concrete sample with a hammer and response is measured in either the time domain or the frequency domain. However, the responses from the frequency domain are more consistent [7].

In the time domain the time (t_c) required for the wave to travel through the sample is obtained from the input and output time spectra. Once the travel time is known the velocity (Vc) can be calculated [11]. For longitudinal waves

$$Vc = L/t_c$$

Once the velocity Vc is known the dynamic modulus can be calculated by using the equation of ultrasonic pulse velocity test

In the frequency domain the resonant or the natural frequency of the concrete sample is determined by the peak value of either the transfer function or power spectral density function [7]. this resonant frequency is then used to calculate the dynamic modulus. For longitudinally vibrated samples having free-free conditions the following equation can be used [11]

$$E = 4(\gamma / g) fn^2 L^2$$

Where
fn = Natural frequency of the sample for the first mode of vibration (Hz)
L = Length of the sample (in)
g = Acceleration due to gravity (ft/s^2)
γ =unit weight of the sample (lb/ft^3)

2.2 Field Testing

There is a variety of nondestructive test equipment available for the in situ evaluation of concrete strength. The operation of these equipments is based on either the wave propagation technique or the surface deflection technique, both techniques are discussed in the following sections.

2.2.1 Wave Propagation Technique

This technique is based on the measurements of the velocity of the Rayleigh waves (surface waves) in a pavement system. Nazarian and Stokoe [10] referred to the method as spectral analysis of surface waves (SASW). This method can be used to determine the modulus and thickness of pavement structure. Low strains are used in SASW .the procedure requires a high degree of sophistication in the field operation and interpretation of the test data [2].
Another example of this type of testing technique is the ultrasonic pulse velocity test, which is a laboratory test procedure as well. In this procedure the dynamic modulus of concrete can be calculated with the help of the pulse velocity, which is explained earlier.

Surface Deflection Technique

In this technique used in pavement testing the associated deflection caused by particular loading conditions are measured. These deflections are used to calculate the modulus value. The test are simple and try to model real load intensities and durations. The modulus computed from the technique is closed to actual conditions.
A large number of surface deflection measurement devices are available. These devices can create different loading condition that are either static or dynamic in nature.
The Benkelman beam and California Travelling Deflectometers are used for static loading conditions. The dynamic equipment imparts either a steady state dynamic (harmonic) load or an impulsive load. Dynaflect and Road Rater are equipments used for steady state loadings conditions that do not have any rest period .Normally some rest period is involved in impulsive load conditions, which can be developed using a falling weight deflectometer (FWD).
For dynamic problems, the selection of either steady state or impulsive load equipment is important and must be made on the basis of actual loading conditions.
Hoffman and Thompson [6] ,Sebaaly et al. [8] , and Tolen et al. [12] , concluded in their studies that "overall " the FWD is the best NDT device for simulating pavement response under a moving load . However ,the major difficulty with this and other dynamic field devices in the method of analysis that consider a static response equivalent to a dynamic response .Moreover the pulse width generated using the FWD is shorter as compared to a moving truck , but the stress and strain developed are comparable to the actual load.

2.3 Indirect Method

Knowledge of the mix design of concrete is used for its evaluation in this method. Some equations and nomographs are available for this purpose, which are discussed in the following section.

2.3.1 The Asphalt Institute

The Asphalt Institute (TAI) regression equation of bituminous mixture that was in the development of their MS-1 Highway Design Manual is:

$$\log_{10} E = 0.553833 + 0.0288229 * P_{200} * f^{-0.17033} - 0.03476 * V_v + 0.070377 * \eta + 0.931757 * f^{-0.02774} + T^{(1.3 + 0.49825*logf)} * ((0.000005 - 0.00189 * f^{-1.1} * {P_{ac}}^{0.5})$$

Where E is the dynamic modulus 10^5 psi; P_{200} is the percent passing No. 200 sieve by weight; V_v is the volume of voids in percent; η is the viscosity of asphalt at 70^0 Fahrenheit (F) temperature in mega poises; f is the frequency of loading, Hz; T is temperature,^{0}F and P_{ac} is the percent of asphalt content by weight. In 1983, Miller, et al. [9] added a correction factor to this equation for a mix type that was develop on the same data set used in this report (combined data for the Asphalt Institute and the University of Maryland). The modified equation is

$$\log_{10} E = 0.553833 + 0.0288229 * P_{200} * f^{-0.17033} - 0.03476 * P_{ac} + 0.070377 * \eta + 0.931757 * f^{-0.02774} + T(1.3 + 0.49825 * logf) * ((0.000005 - 0.00189 * f^{-1.1} * ((P_{eff} - P_{opt.eff} + 8) * 0.483)^{0.5}$$

Where $(P_{eff} - P_{opt.eff} + 8) * 0.483$ is the equivalent to $(P_{ac} - \infty)$. In this equation, ∞ is a correction constant incorporated in the original equation to account for widely different ranges of an optimum asphalt contents found in the combined data set. The parameter P_{eff} , is the percent of effective asphalt content by volume while $P_{opt.eff}$ is the effective asphalt content at optimum design condition.
In conjunction with the work of Miller, et al. by applying a correction factor (∞) to the original regression model, a more in depth statistical study of all E data point (combined TAIUM results) was conducted (Witczak, Akhtar modification No.3) to improve the model [3]. This work resulted in the development of to separate the predictive equations that increased the R^2 from 0.93 (Model 1) to $R^2 = 0.95$ (Model 2). Where R^2 is co-efficient of variation. The main change in these equation compare to previous one indicated, was the direct inclusion of the gradation term of the aggregate blend into the regression.
The two models are;

Model 1:

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$$\log_{10} E = 1.41224 - 0.02247552 * P_{air} + 0.01229677 * P\ 3/4 + 0.0633417 * \eta - 0.00728469 * T + 0.145700 * \log f + 0.0000196085 * \log f * T^2 - 0.0000282528 * (P_{eff} - P_{opt.eff} + 8) * 5 * T^2 - 0.000142367 * P_{eff} * P_4 + 0.00623413 * P_{200} * P_{abs}$$

Model 2:

$$Log\ E = 2.468 - 0.1155 * P_{eff} - 0.0299 * P_{air} - 0.0975 * P_{200} - 0.00963 * P_4 + 0.360 * P_{abs} - 0.00815 * T + 0.0660 * f - 0.0000618 * T^2 + 0.00253 * P_{eff} + 0.0083 * P^2{}_{200} - 0.00164 * \frac{P^3}{4} - 0.000308 * \frac{P^2 3}{8} + 0.000204 * P^2 4 - 0.105 * P^2 abs + 0.0171 * \eta^2 - 0.00268 * f^2 + 0.00167 * P_{\frac{3}{8}} * P_{eff} + 0.000709 * P_{3/4} * P_{eff} + 0.000937 * P_{3/4} * P4 - 0.00069 * P_{3/8} * P_4 - 0.0031 * P_{3/4} * P_{abs}$$

With

T: Test temperature (degrees Fahrenheit)
f: load rate – frequency (Hz- cps)
P_{air}: (V_v): % Air voids by volume
P_{200}: % passing No. 200 sieve (total aggregate weight)
$P_{3/4}$: % retained ¾'' sieve (total aggregate weight)
$P_{3/8}$: % retained 3/8'' sieve (total aggregate weight)
P_4: % retained No.4 sieve (total aggregate weight)
P_{abs}: % asphalt absorbed (by weight of aggregate)
P_{eff}: % effective asphalt content by volume (total mix)
$P_{opt.eff}$: P_{eff} at optimum asphalt conditions by volume (total mix)
η = Asphalt viscosity at 70°F (in 10^6 poises).

2.3.2 Shell Nomograph

The widely utilize shell method was developed from experimental work and presented in nomograph form. This resultds in the prediction of stiffness (asphalt modulus) for a given volume concentration of aggregate, bituminum content, and a given bituminum stiffness, [3]. The accuracy of the nomograph , as checked by extensive measurements on a large number of different asphalt mixes , is factor of 1.5 to 2. This variation is dependent on a number of factors that are very difficult to take into consideration in nomograph solution. At low stiffness values of asphalt mix (lower than 10^8 N/m^2) at a high temperature and or long loading times , the modulus depends not only on the parameters mentioned above , but also on the nature and grading of the aggregate , the influence of which is considerable.

Different methods in the form of nomographs are available for estimating the asphalt and mixture stiffness module. Van der poel , H eukelom and Van der poel , and McLeod are some of the examples of these methods [1].

3 RECOMMENDATIONS

Considering the national economic conditions it is important to evaluate the paving material with a high degree of accuracy to avoid over designing or under designing problems.

Presently several testing procedures are on the market for evaluation purpose but none has proven to be totally effective [7]. In this situation use of more than one NDT technique for prediction, the dynamic modulus is becoming popular in many countries. However, in some instances the use of more than one method is not advocated because of economic considerations versus the possible marginal increase in accuracy of predicting the modulus value. Under these circumstances the use of I.L.T with instrumented hammer and F.F.T analyzer is recommended because of its accuracy in predicting the effect of all factors that affect the dynamic modulus of asphalt concrete [7]. However, above 73°C, the use of I.L.T., is not recommended and thus requires more research.

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