CHAPTER 3 – BACKGROUND

Current mechanistic design procedures are based on modeling pavement as an elastic multi-layered system. Estimating the remaining life of flexible pavements is mainly based on predicting the strains or stresses at the interfaces of different layers. The two main strains considered are the tensile strain at the bottom of the AC layer and the compressive strain on top of the subgrade (Huang, 1993). These critical strains are strongly related to the moduli of all pavement layers.

Daniel and Kim (1998) defined several field and laboratory tests for determining AC moduli. The most common laboratory tests are the resilient modulus, creep, uniaxial frequency sweep, free-free resonant column, and ultrasonic wave velocity tests. The main field tests are the Falling Weight Deflectometer (FWD) and wave propagation (or seismic) tests.

Resilient modulus tests have been used by many researchers to measure the modulus of Hot Mix Asphalt (Roberts et al., 1996). These tests can be performed either in compression (similar to soil specimens) or diametrically. The diametral resilient modulus test will be discussed comprehensively in the next section since it was used in this study.

In the creep test, the specimen is subjected to a static load. The displacement of the specimen due to the applied load is measured with time. Using the variation in compliance (ratio of the strain and stress) with time, and the time-temperature superposition principle (Kim and Lee, 1995), the relaxation modulus can be determined and converted to a modulus.

In the uniaxial frequency sweep test, also known as the complex modulus test, the stresses and strains under sinusoidal loading are measured (ASTM D3497). Assuming that the material is linear viscoelastic, the dynamic modulus and viscous damping (or storage and loss moduli) are determined. By varying the frequency over a wide range, the variation in modulus with frequency can be determined. The method can be effective over a range of frequencies from 0.1 Hz to 50 Hz.

In the free-free resonant column test, also know as the impact resonance test, the specimen is impacted with a hammer, and the resonant frequency associated with the standing waves within the specimen is measured. The resonant frequency, along with the length of the specimen, can be used to determine the modulus (ASTM C215).

The ultrasonic wave velocity method will be discussed comprehensively in the next section. This method was used in this study.

Most of the laboratory tests discussed above are comprehensive and time-consuming. As such, they are not suitable for testing a large number of specimens. The free-free resonant column test is quite rapid. For this test to be effective, a specimen with a length-to-diameter ratio of at least two is required. Since preparing such specimens from the thin pavements tested in this study was not reasonable, this test method was not considered.

Several parameters affect the modulus of bituminous materials. The most important parameters are the rates and frequency of loading, temperature, air void content, binder content and gradation. The impact of each of these parameters is well published. An excellent review of this matter can be found in Roberts, et al. (1996).

Daniel and Kim (1998) and Kim and Lee (1995) used the results from several laboratory and field tests (such as FWD, ultrasonic, uniaxial sweep, and creep) to show the frequency-dependency of modulus. Aouad et al. (1993) clearly demonstrated the importance of considering the rate of loading. At a temperature of 77^{O}F, the modulus measured with seismic methods should be reduced by a factor of about three to account for the rate of loading.

The AC modulus is strongly dependent on temperature. Von Quintus and Killingworth (1998) demonstrate the importance of temperature correction, and the complexity involved in considering the temperature gradient within a pavement section. Aouad et al. (1993), Li and Nazarian (1994), and several other investigators have studied the variation in modulus with temperature for seismic methods.

METHODOLOGY FOR QUALITY CONTROL BASED ON SEISMIC METHOD

Nazarian et al. (2003) have proposed a comprehensive protocol for quality management of the ACP based on seismic methods. The proposed quality management procedure consists of five steps. The first step consists of selecting the most suitable material or mix for a given project. In the second step, a suitable modulus value is determined based on variation in modulus with the primary parameter of interest. For a particular hot mix asphalt (HMA) mixture, this step may consist of developing an air voids vs. modulus curve. In the third step, the variation in modulus with environmental factors is considered. In the case of an HMA layer, the variation in modulus with temperature is important. The fourth step consists of determining the design modulus for the material. The fifth and final step is to compare the field modulus with the acceptable laboratory modulus. All steps are briefly described below.

Step 1: Selecting the Most Suitable Material

Even though the durability of a material cannot be directly included in the structural design of a pavement, the durability definitely does impact performance. The process of volumetric design, from the simplest Marshall method to the most sophisticated, Strategic Highway Research Program (SHRP) method, ensures a constructible and durable material. However, the material selection and mix design should be based on the existing collective experience within the highway community. The following steps, even though more quantitative, do not replace this knowledge.

Step 2: Selecting the Most Suitable Moduli

After the material is selected and its constructability is ascertained, the next step is to determine its most suitable modulus. The modulus can be related to one of the primary construction parameters such as the compaction effort (i.e., air voids) similar to Figure 1. Two modulus values should be selected from the seismic modulus-air voids curves: the modulus corresponding to the air voids at placement (typically 7-8%), and the modulus at design air voids from the job mix formula (JMF, typically 4%). The modulus at placement is used by the construction engineer for field quality control as described in Step 5. The modulus at the design air voids is used by the pavement engineers to determine the modulus that should be used in structural design as discussed in Step 4.

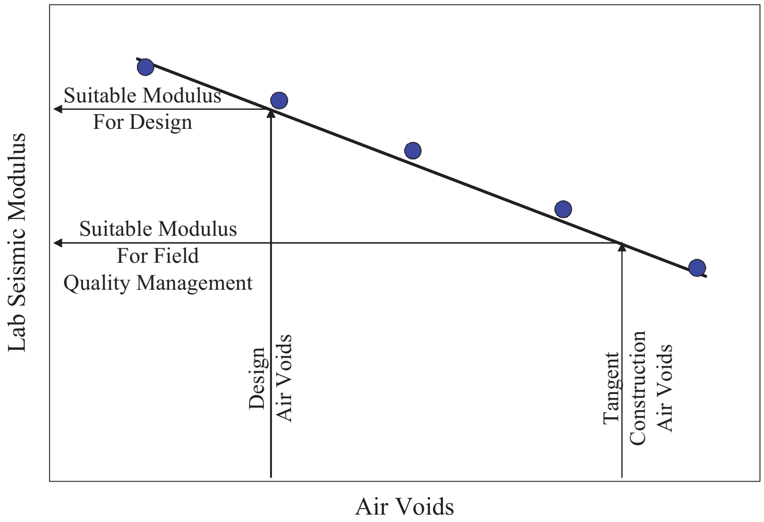

Figure 1. Graph. Process of Determining Most Suitable Moduli.

Step 3: Characterizing the Variation in Modulus with Temperature

After the compaction of a layer is completed, it may be exposed to different temperatures. The simplest method of relating modulus to temperature consists of preparing two specimens: one at the JMF air voids and another at the target placement air voids. These specimens are subjected to a sequence of temperatures. The suitable temperature range for the region being considered can be determined based on the guidelines set forward by SHRP for selecting the regional air temperature extremes to determine the appropriate PG grade for the binder. At the end of each temperature sequence, the specimens are tested as described in the next sections. An example for the variations in modulus with temperature for one mixture is shown in Figure 2.

Step 4: Determining Design Modulus of Material

The most suitable seismic modulus at JMF air voids, determined in Step 2, should be translated to a design modulus as will be discussed in the next section. As schematically shown in Figure 3, the most rigorous way of calculating the design modulus is to develop a master curve as advocated by the new 2002 Pavement Design Guide funded by the National Cooperative Highway Research (NCHRP) under Project 10-37.

If the modulus assumed by the designer and the one obtained from this analysis are significantly different, either an alternative material should be used, or the layer thickness should be adjusted. In that manner, the design and material selection can be harmonized.

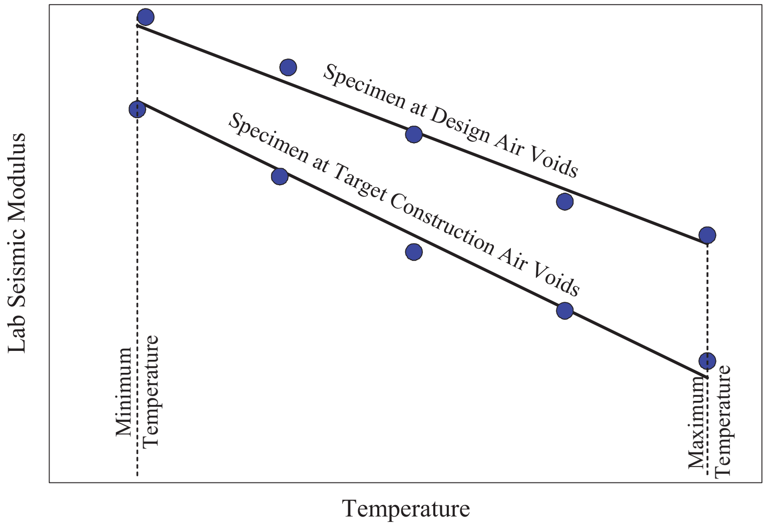

Figure 2. Graph. Process of Characterizing Variation in Modulus with Temperature.

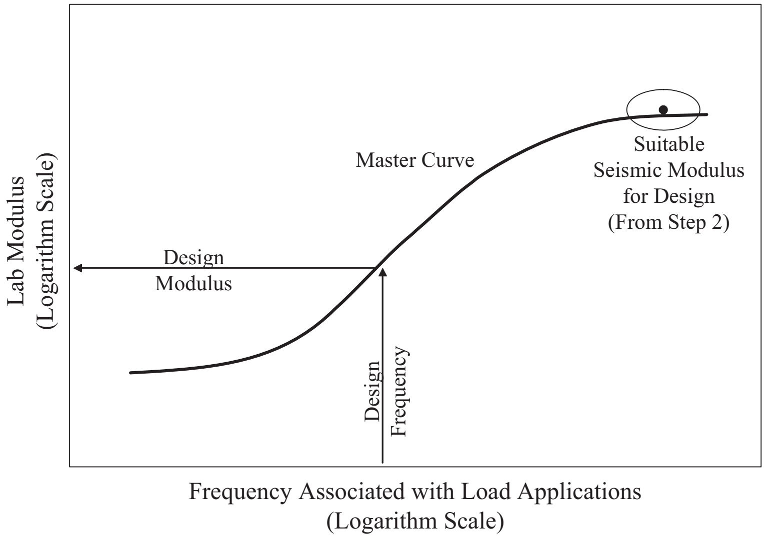

Figure 3. Graph. Process of Estimating Design Modulus.

Step 5: Field Quality Control

Tests are carried out at regular intervals or at any point that the construction inspector suspects segregation, lack of compaction, or any other construction related anomalies. The field moduli should be greater than the most suitable laboratory seismic modulus determined at the placement air voids in Step 2. An example is shown in Figure 4.

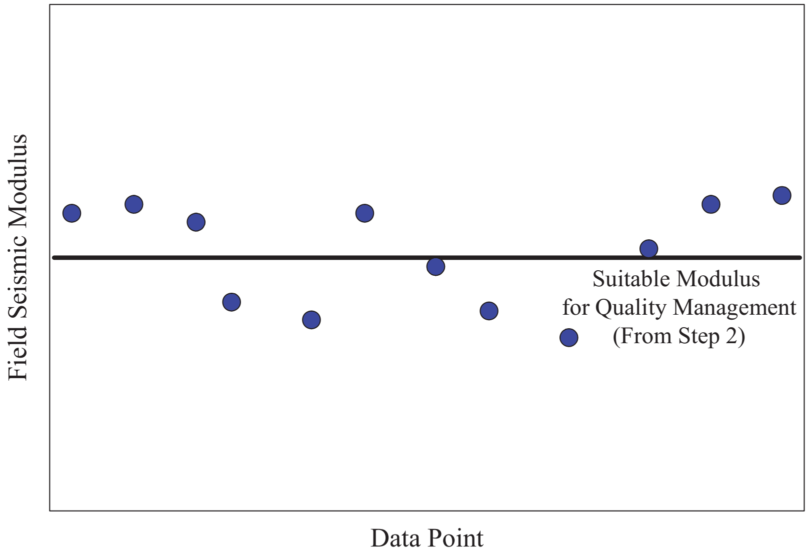

Figure 4. Graph. Process of Field Testing for HMA Materials.

As emphasized in Step 2, it is important to make a distinction between the most suitable modulus for design reported to the pavement engineer and the most suitable modulus used as a guideline for quality management.

The procedure described above was adapted to the study described here. The methodology followed is described in Chapter 4.

DESIGN MODULUS FROM SEISMIC MODULUS

Moduli obtained with seismic measurements are low-strain high-strain-rate values. Vehicular traffic causes high strain deformation at low strain rates. Because of the difference, there has been concern in the pavement community regarding how to implement seismic moduli in the design. This concern has been resolved by implementing a master curve concept, which tracks modulus over a wide frequency range.

The most desirable way of calculating the design modulus is to develop the master curve based on the recommendations of Witczak et al. (1999). The response of a viscoelastic material, such as AC, is dependent on the loading frequency and temperature. The general practice has been to perform the testing at various temperatures with similar loading frequencies. A master curve is generated at a reference temperature by using time-temperature shift factors. The following sigmoid function proposed by Ferry (1970) can be used to generate a master curve

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \times \log t_r}} \tag{3.1}$$

where E* = dynamic modulus, t_r = loading period, δ = minimum value of dynamic modulus, δ + α = maximum value of dynamic modulus, and β and γ = sigmoidal function shape parameters. Once the master curve is established, the design modulus can be readily determined from the design vehicular speed and the design temperature as recommended in the 2002 Design Guide.

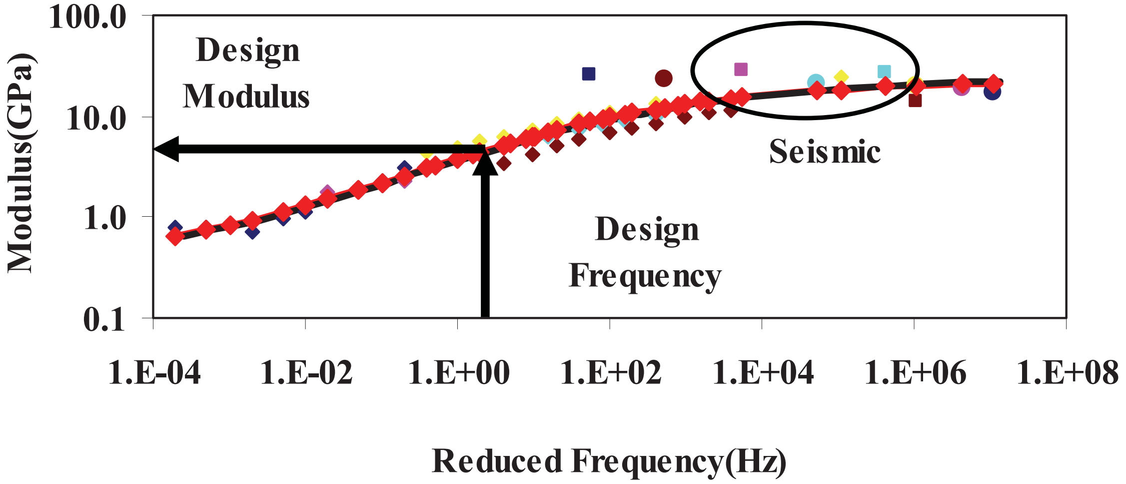

Figure 5. Graph. Master Curve Concept for Defining Design Modulus.

Tandon et al. (2004), have shown that the seismic modulus and the master curve from complex modulus correlate well. Typical results from one material when the seismic and dynamic moduli are combined are shown in Figure 5. First, a reference temperature is defined for the region. A design frequency is then determined based upon the vehicular speed. The desired design modulus based on these two input parameters can readily be determined from the master curve, as shown in the figure.