Improved Ultrasonic Pulse Velocity Technique for Bituminous Material Characterization

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ABSTRACT

An efficient quality control and acceptance (QA/QC) procedure for constructing hot mix asphalt (HMA) pavements requires the complimentary use of traditional destructive test methods and innovative non-destructive testing (NDT) methods. Current wave-based NDT methods are efficient and economical for the evaluation of material properties. For instance, the ultrasonic pulse velocity (UPV) method is one of the most common NDT methods used for material characterization. However, its isolated use for predicting material strength is limited because of the different variables that affect the strength-velocity relationship. Wave velocity alone does not provide complete information of the materials strength. Thus, additional wave characteristics such as wave attenuation as a function of frequency should be also considered to complement the wave velocity information.

In this study, three signal processing techniques: Fourier transform, short-time Fourier transform, and the wavelet transform are used to analyze wave attenuation and frequency content to develop a suitable condition index for HMA mixtures based on wave characteristics. The relative condition of HMA mixtures is evaluated by considering three wave attenuation parameters: peak-to-peak amplitude, spectral area, maximum spectral amplitude. The results of UPV tests are compared to the standard dynamic modulus test for selecting the most suitable condition index. The results indicate that the condition index based on the amplitude measurement has the potential to provide a reliable assessment of the quality of HMA mixtures.

1 INTRODUCTION

The long-term pavement performance (LTPP) of HMA mixtures depends on numerous variables, e.g. properties and quality of the materials used; quality of design and construction; and appropriate maintenance activities. The fact that so many variables affect LTPP would require the in-situ properties of HMA mixtures to closely reflect the designed mix properties determined from short-term laboratory performance tests, and accurate monitoring of pavement sections to provide a systematic assessment of pavement condition. Therefore, the in-situ condition assessment of pavement structures is a critical step for ensuring compliance. Furthermore, highway transportation agencies are moving towards the use of innovative non destructive testing (NDT) methods for evaluating the in-situ condition of pavement structures. Therefore, a reliable quality control and acceptance protocol based on NDT is needed to ensure that pavements are constructed according to the HMA mix design. It is anticipated that the simple performance tests (SPT) recommended by the Federal Highway Administration (FHWA) [1, 2, 3, 4] will play a key role in the development and calibration of NDT methods suitable for in-situ pavement condition assessment.

Various NDT methods have been developed and applied in engineering with different degrees of success [5, 6, 7, 8, 9]. Over the years, NDT methods based on seismic wave propagation have gained increased use and popularity. Current wave-based NDT methods such as ultrasonic pulse velocity, impact echo, and spectral analysis of surface waves (SASW) have been used for the in-situ evaluation of material properties. However, there are some limitations in each of these NDT methods when they are used individually. These limitations have not been fully studied and understood. For example, the ultrasonic pulse velocity (UPV) method is one of the most commonly used wave-based methods in NDT. Yet, its potential for assessing the quality of materials is limited because of the different variables that affect the relationship between strength and velocity. This may be the reason why a poor correlation between the wave propagation parameters determined from the standard pulse velocity test method (ASTM C597) and the field rutting was reported by the FHWA, NCHRP Report 465 [1]. Improved techniques for processing the output signals such as the spectral analysis of attenuation are necessary to complement the strength-velocity data. The main objective of this paper is to present preliminary results of an experimental program carried out to address the current deficiencies of the UPV method to improve the reliability, accuracy and consistency for bituminous material characterization both in the laboratory and in the field.

2 THEORETICAL BACKGROUND

2.1 Nondestructive testing using seismic waves

Seismic motion in a semi-infinite medium can propagate in the form of body waves and surface waves. Body waves include compression waves and shear waves. In contrast to body waves, surface waves or Rayleigh waves are confined to a zone near the surface of the semi-infinite medium and propagate near the boundary of the semi-infinite medium.

Wave velocity depends on the elastic modulus and mass density of the medium; whereas, the change in amplitude of a wave front (attenuation) depends on the attenuation mechanisms present in the medium (e.g. friction, spreading, scattering, viscous flow, mode conversion). The change in wave velocity is typically used to assess the condition of materials [ASTM C 597-97]. In some cases, however, wave velocity in two different mediums could be almost constant, whereas wave amplitude could change significantly. Different NDT techniques that have been used for material characterization include ultrasonic pulse velocity (UPV), impact echo, spectral analysis of surface waves (SASW), and transmission coefficient (TC) [10, 11, 12, 13]. This study focuses on the use of UPV method and the use of different signal processing techniques for improving the accuracy of assessing the integrity of asphalt concrete.

In UPV method, a pulse wave emitted by a transmitter propagates through the material and is detected by a receiver as shown in Figure 1. The propagation of low-strain mechanical waves assesses the state of materials without causing permanent deformations. The travel time of the stress pulse and the distance between transducers are precisely measured to compute the wave velocity. The propagating pulse is generally reflected by surface boundaries, and/or flaws. Multiple reflections of stress pulse between the surfaces or flaws, give rise to patterns of wave reflection and transient resonance, which can be identified in the frequency spectrum, and used to evaluate the integrity of the material.

When the wavelength is significantly longer than the internal scale of the material, propagation parameters (wave velocities and attenuation) can be defined for an equivalent continuum. The group shear and compressional wave velocities V_S and V_P are given by

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

$$V_P = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (2)$$

Where G is shear modulus, M is constraint modulus and ρ is mass density of the medium. The velocities of compressional and shear wave velocities are related through Poisson's ratio ν as shown in Equation (3).

$$\frac{V_P}{V_S} = \sqrt{\frac{2(1-\nu)}{1-2\,\nu}} \qquad (3)$$

If the medium is homogeneous, all the frequency components of a pulse travel at the same speed given by Eqs. 1 and 2. However, if the medium is dispersive, the propagation of each frequency component has a different velocity. The velocity of the pulse is referred to as group velocity; whereas, the velocity of each frequency component is called phase velocity. In this paper, the study of wave attention is focused on P- waves only.

Figure 1 shows a typical UPV test where, a single square pulse is sent through the specimen. The output signal is analyzed in both time and frequency domains. In the time domain, group velocities for P- waves are evaluated; whereas, phase velocities and spectral attenuation coefficients are evaluated in the frequency domain.

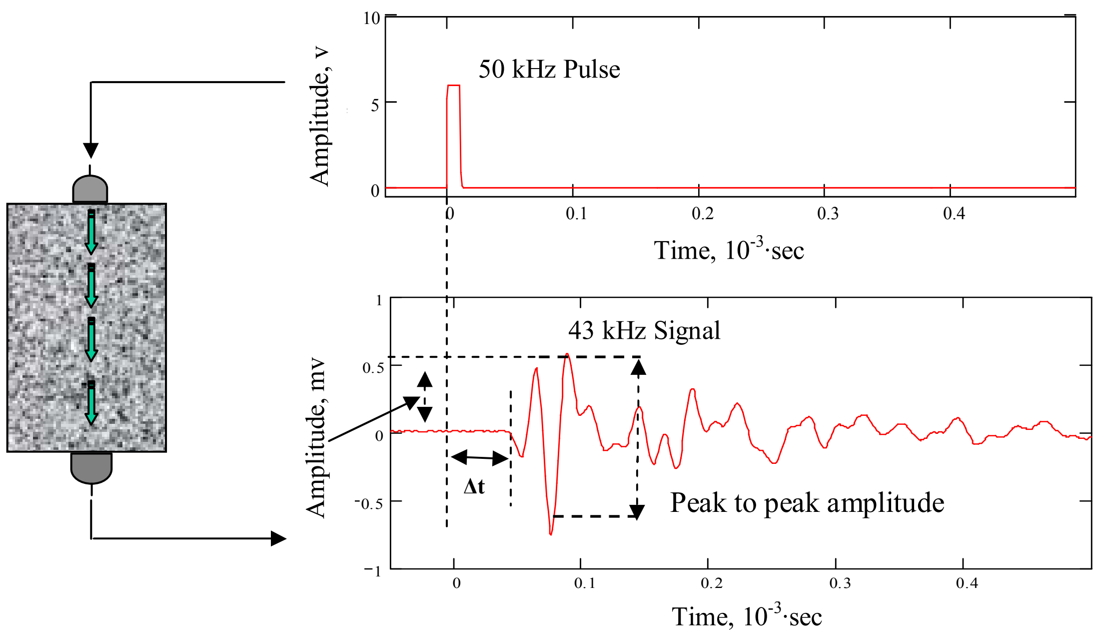

Figure 1: Typical UPV testing on an asphalt concrete briquette

In the laboratory, signals are recorded in the *time domain*. The transformation from time domain to frequency domain is done using a mathematical tool called “Fourier transform”. Specifically, in this study, three different methods: Fast Fourier transform (FFT), Short Fourier transform (SFT), and the Wavelet transform (WT) are explored to characterize the output signal. These methods are briefly described in the following sections. After the transformation, the wave attenuation and frequency content in the frequency domain are analyzed. To eliminate the effect of reflections and the effect of shear wave and Rayleigh waves, the arrival of P-waves (first arrival) is selected by widowing the time signal as indicated in Figure 2.

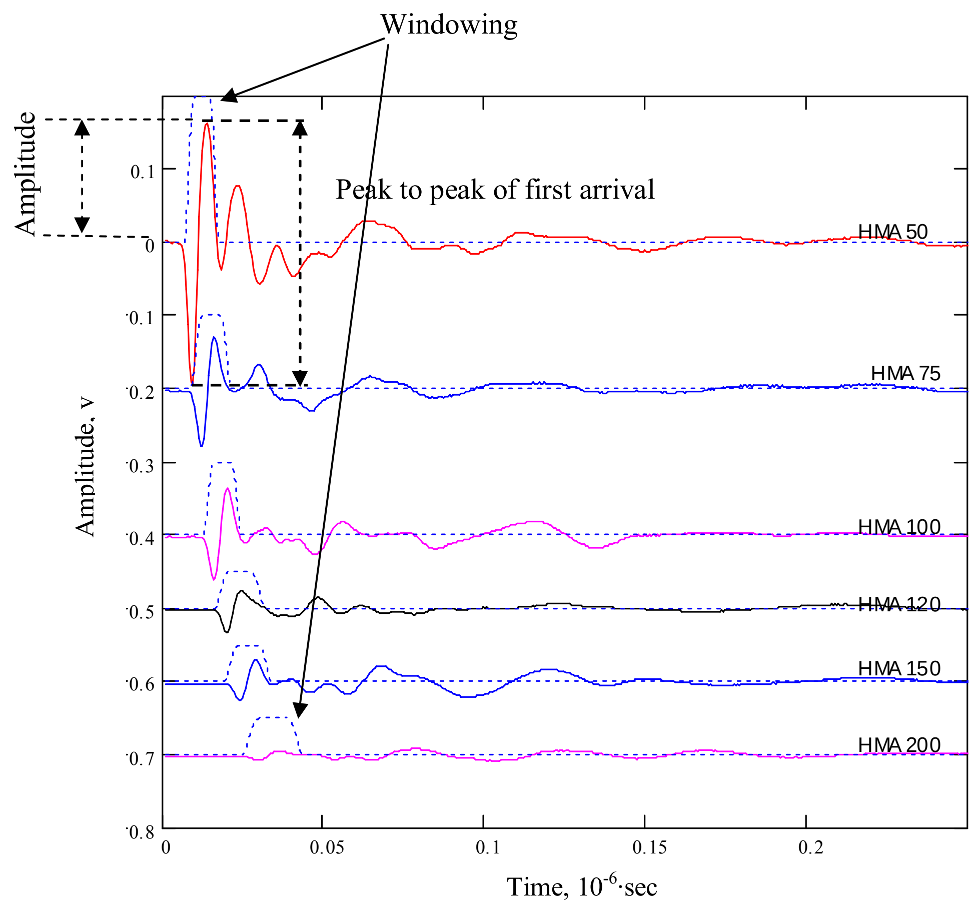

Figure 2: Selection of first arrival by windowing for HMA specimens of different lengths
(Note: HMA 50 = Hot mix asphalt specimen of 50 mm length)

Fast Fourier transform (FFT): Every signal or waveform can be expressed as a summation of sine waves and cosine waves with appropriate amplitude and phase by using the Fourier transform (FT). The Fast Fourier Transform (FFT) is a computationally fast algorithm to compute the Fourier transform of discrete signals.

Short Fourier Transform (SFT): The FFT doesn't provide information about the change in frequency with time. In reality, signals do have frequency components that change with time. To evaluate the variation of the frequency component with time, the Short Fourier transform (SFT) is used. Figure 3 shows the use of SFT on a typical output signal. First, the signal is divided into short segments by windowing. The FFT is computed on the windowed signal. Each frequency spectrum shows the frequency content within each window. As the window moves along the signal, the successive spectra shows the evolution of the frequency content with time. A short time segment is often sufficient to capture the spectral information at high frequencies. However, for low frequencies, a longer time segment is necessary. The window size thus controls the tradeoff between frequency resolution and time resolution.

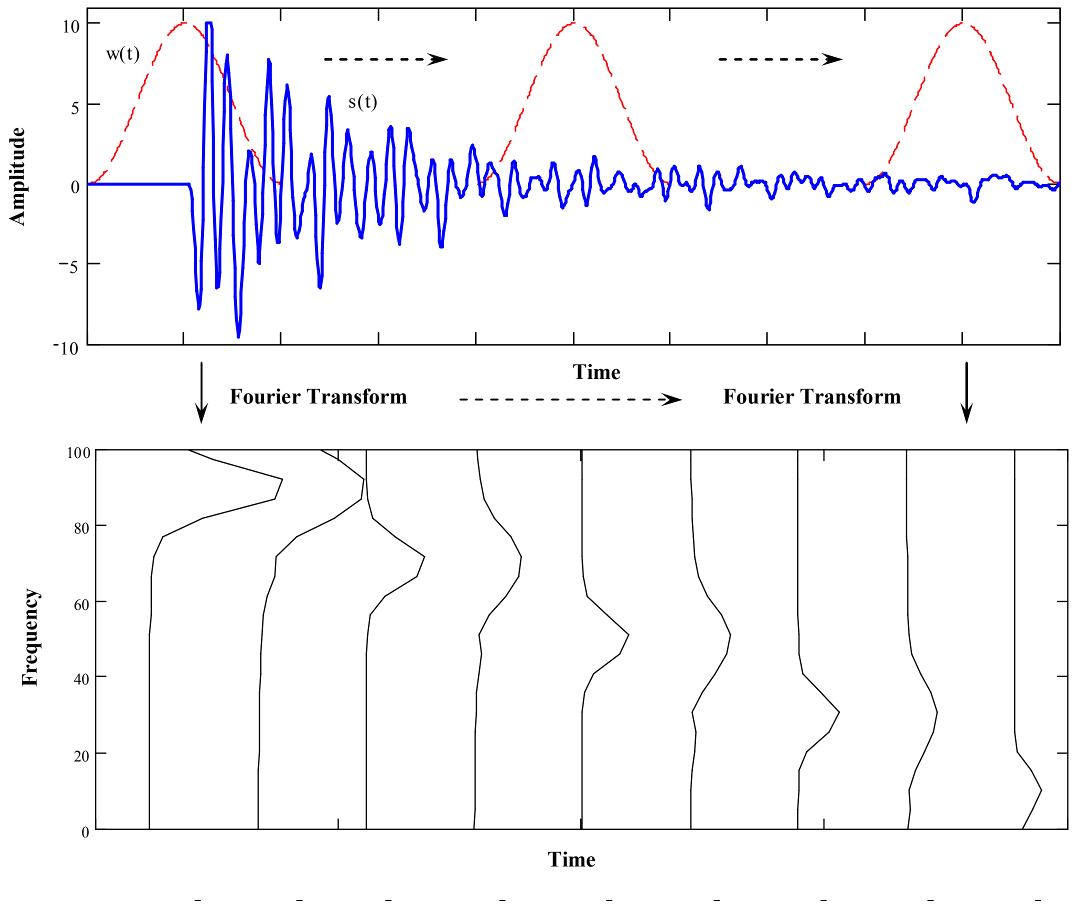

Figure 3: Use of the Short Time Fourier Transform

Wavelet Transformation: The wavelet transformation is considered an improvement to SFT. The SFT transform cannot be used to precisely measure low frequency if the window is small (Figure 4). If a large window is used to capture low frequencies, resolution in time is lost. To address this problem, a family of windows with varying sizes is generated to provide a collection of time-frequency representations of the signal with different power spectral values. An optimum window size is selected to provide the maximum power spectrum for the signal recorded by the receiver. This approach is called a wavelet transform.

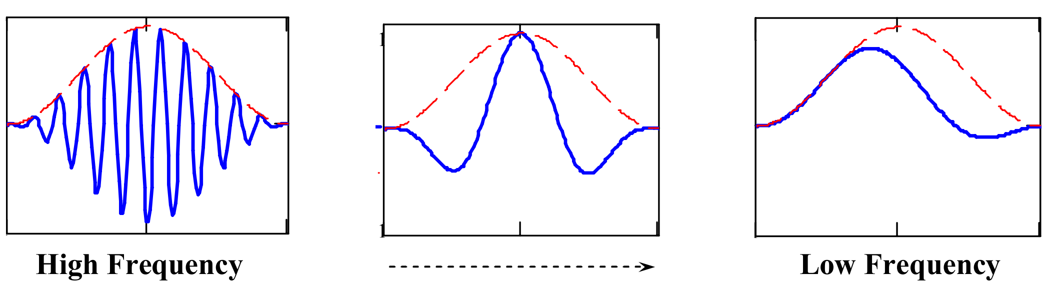

Figure 4: Effect of fixed window size on capturing different frequencies.

2.2 Wave attenuation and frequency content analysis

When windowed waves travel through a medium, its energy or intensity diminishes with distance. In idealized materials, the signal amplitude is only reduced by the spreading of the wave. Natural materials, however, all produce further weakening results from two basic causes: scattering and absorption. Scattering is the reflection of the wave in other directions than its original direction of propagation [5]. Absorption is the conversion of the mechanical energy into heat. The combined effect of scattering and absorption produces wave attenuation. Therefore, ultrasonic attenuation represents the decay rate of the wave as it propagates through material. Attenuation often serves as a measurement tool that leads to the formation of theories to explain physical or chemical phenomenon, which decreases the ultrasonic intensity. The amplitude change of a decaying plane wave can be expressed as:

$$A(x) = A_o e^{-\alpha x} \tag{4}$$

where, $\mathbf{A_0}$ is the amplitude of the propagating wave at some location. The reduced amplitude **A** depends on the travel distance x and the attenuation coefficient which depends on the type of material.

The attenuation coefficient increases with frequency, thus high frequencies (small wavelengths) attenuate faster than low frequencies. On the other hand, the damping coefficient D is used to measure the medium attenuation per radian and it is generally considered frequency independent. This coefficient is expressed in terms of the spectral amplitudes $A_1(f)$ and $A_2(f)$ at two different locations as a function of frequency, f, by

$$D = \frac{1}{\Delta\phi(f)} \ln\left[\frac{A_1(f)}{A_2(f)}\right] \tag{5}$$

where, $\Delta\phi$ is the phase difference for the given frequency.

2.3 Parameters used for wave characterization

Four different parameters are used to characterize the output signal values: peak-to-peak amplitude, spectral area, maximum magnitude of the frequency spectrum, and group velocity. The peak-to-peak value is the difference between the maximum and minimum values of the windowed signal in time. The area of the frequency spectrum is the area under the frequency curve corresponding to the windowed signal. Velocity is computed using the first wave arrival as distance over time.

3 EXPERIMENTAL PROGRAM AND THE RESULTS

The goal of the experimental program is to develop a suitable signal processing technique for determining the wave attenuation characteristics that are most highly correlated to the quality of the mix. Initially, the specimens were compacted using the Superpave gyratory compactor at different number of gyrations to produce specimens of different volumetric properties. It has been shown in the literature that the percent compaction increases with the number of gyrations for a given mixture and so the quality of the specimen [6]. The correlation among the wave attenuation characteristics, density, and the number of gyrations were examined as a first step. Based on these results, the potential correlation between the fundamental property such as the dynamic modulus and the wave characteristics was explored for the selection of the most suitable parameter for assessing the mix integrity.

The experimental program involved three steps. The first step included calibrations of the sensors used in the experiment. In the second step, different signal processing techniques were explored to select the most suitable method for characterizing the output signal that could be used for condition assessment of asphalt concrete mixes. In the third step, dynamic modulus tests were conducted. The relationship between the dynamic modulus and the wave characteristics was examined for the selection of the most suitable parameter. The following sections describe briefly the three different steps involved in the experimental program.

3.1 Calibration

The purpose of calibrating the wave velocity measurements is to eliminate the measurement error due to the time delay associated with the mismatch of impedance between the transducer and the specimen. This error depends on the type of material tested.

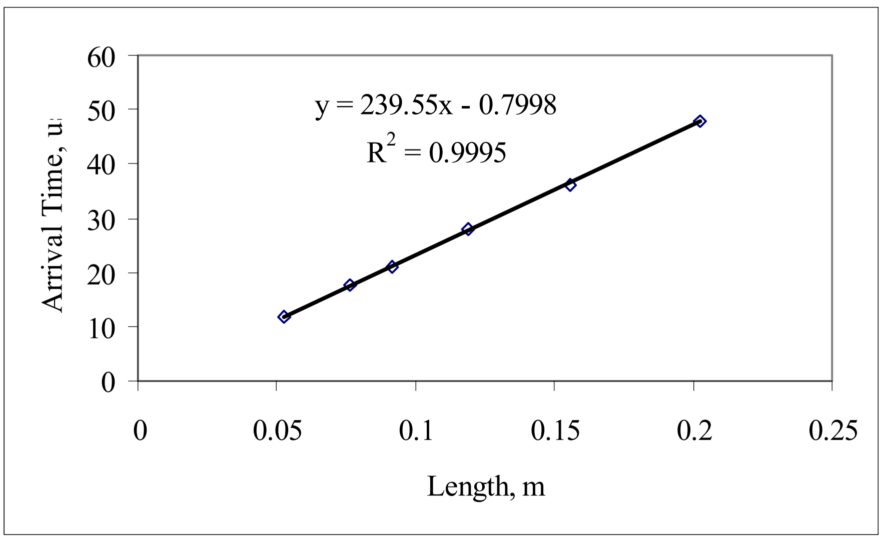

Figure 5: Calibration Using HMA for 1MHz Transducers

The calibration was carried out by measuring the travel time and the velocity of P waves through the HMA specimens of different lengths. Figure 5 shows the relationship between the measured velocity and the specimen length for the HMA specimens used in the experiment. A strong correlation (high R^2) between the travel time and the bar length was observed as seen in Figure 5.

The 'y' intercept of the regression line is -0.7998 and it represents the specific delay time due to the mismatch of impedance between the transducers and the asphalt specimen. This delay time was subtracted from the observed time in order to estimate the actual travel time.

3.2 UPV Testing

An experimental program was designed to study the relationship between the wave characteristics of seismic waves used in the UPV test and the quality of the asphalt concrete specimens prepared in the laboratory. The plant mix (Superpave 19 mm) from Hwy 26 in southern Ontario was used to prepare samples required for testing. This mix is equivalent to the heavy duty binder mix commonly used in southern Ontario.

Six cylindrical briquettes of 150 mm diameter were compacted at each of the following gyration levels: 40, 60, 80, 100, 120, and 140. Out of these briquettes, the test specimens of 100 mm diameter were cored from the center of the 150 mm diameter gyratory compacted briquettes. The ends of all test specimens were sawed to provide a smooth surface perpendicular to the axis of the specimen.

Figure 6 shows the experimental set up of the UPV test conducted in the laboratory. An ultrasonic laboratory device using a v-meter was used for testing asphalt specimens. In this device, the electric pulse was transformed into mechanical vibration through a transducer coupled to one end face of the specimen. A receiving transducer is securely placed on the other end face of the specimen, opposite the transmitting transducer. The receiving transducer, which senses the propagating waves, is connected to an internal clock on the device. The clock automatically displays the travel time of compression wave. By dividing the length of the specimen by the travel time, the compression wave velocity of the material is determined. Adequate care was taken to ensure that constant pressure was applied consistently on the transducer to ensure good contact between the transducers and the specimens to provide reliable and consistent data. The results of the UPV test are discussed in the following sections.

Figure 6: Ultrasonic pulse velocity (UPV) test

3.3 Dynamic Modulus Test

A dynamic modulus test involves applying a sinusoidal (haversine) axial compressive stress to an asphalt concrete specimen at a given temperature and loading frequency. The applied stress and resulting recoverable axial strain response of the specimen is measured and used to calculate the dynamic modulus. The values of dynamic modulus can be used as a measure of asphalt concrete performance.

The relationship between stress and strain for a linear viscoelastic material is defined by a complex number called "complex modulus" (E^*). Its absolute value calculated by dividing the maximum stress (σ_o) by the recoverable axial strain (ε_o) is defined as dynamic modulus ($|E^*|$):

$$|E^*| = \sigma_o / \varepsilon_o \quad (6)$$

The real and imaginary components of the complex modulus can be expressed as:

$$E^* = E' + iE'' \quad (7)$$

In general, E' is the storage or elastic component of the complex modulus; while E'' is the loss or viscous component. The angle by which ε_o lags behind σ_o is defined as the phase angle (N), which is an indicator of the viscous properties of the material. For a pure elastic material, N = 0, and the complex modulus E^* is equal to the absolute value or dynamic modulus. For pure viscous material, N = 90^o. The dynamic modulus test is performed at loading frequency of 0.1, 0.5, 1.0, 5, 10, and 25 Hz at different temperatures. Initially, the test was conducted at an ambient temperature of 22 ^{o}C. The loading is applied from 25 Hz to 0.1 Hz according to the recommended procedure by FWHA [1]. Figure 7 shows the experimental set up for the dynamic modulus test using the Interlaken testing equipment.

Figure 7: Dynamic modulus test

4 RESULTS AND DISCUSSIONS

4.1 Relationship among gyration, density, velocity, and elastic modulus

Figure 8 shows that a reasonable correlation exists between the number of gyrations and the density. However, in some cases, a lower gyration (e.g. at 80) produced a higher density than the value obtained at a higher gyration (e.g. at 140) for the same mix. This unusual result could be due to a number of reasons such as different compaction temperatures, aggregate segregation while sampling from different batches, etc. This appears to point out that density is not always a good indicator of workmanship. Therefore, a suitable parameter in addition to the density measurements is needed for quality assurance of HMA mixes. The observed moderate correlation between the velocity and the gyration (Figure 9) appears to support the previous findings that the wave velocity of seismic waves may not be adequate enough to assess the quality of different HMA mixtures [1].

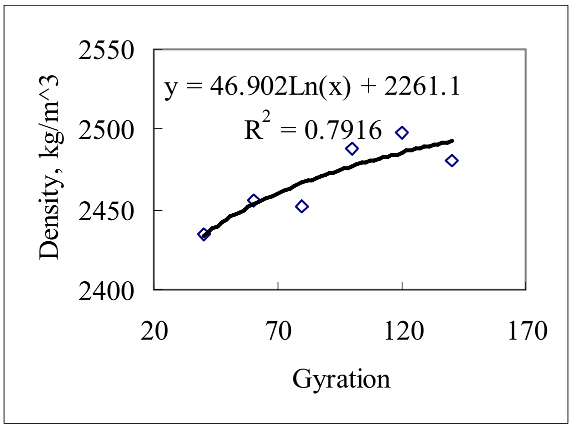

Figure 8: Density vs. gyration

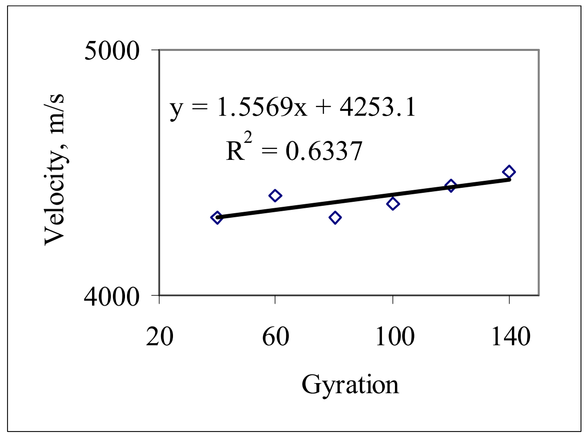

Figure 9: Velocity vs. gyration

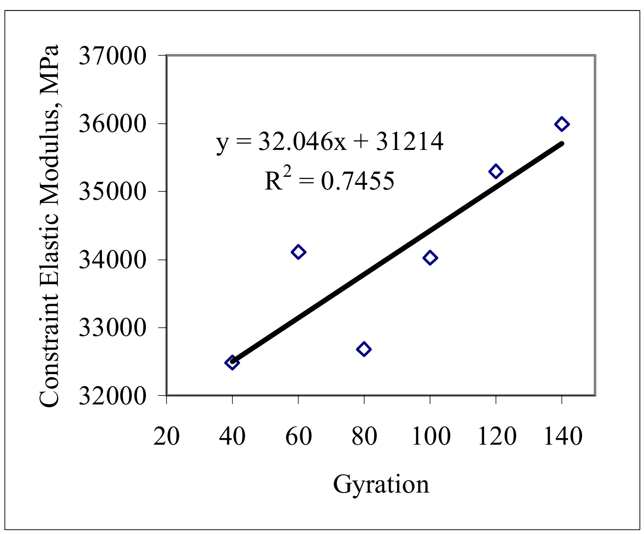

Figure 10: Constraint modulus from wave velocity vs. gyration

The constraint elastic modulus of the mix from the wave velocity based on Eq. 2 was determined for different gyrations and the results are shown in Figure 10. The correlation of the elastic modulus with the number of gyration appears to be slightly better than that observed for the velocity. However, further improvement is needed to increase the level of confidence for use as pavement performance measures.

4.2. Relationship between wave characteristics and the number of gyrations

Figures 11-13 show good correlations between the number of gyrations and the wave characteristics such as peak to peak amplitude, the spectral area, and the magnitude. This observation strongly supports the concept that seismic wave technique has the potential for assessing the integrity of the HMA material.

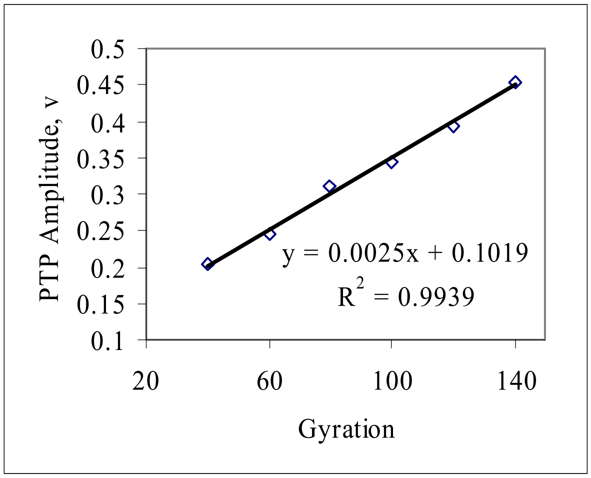

Figure 11: PTP amplitude vs. gyrations

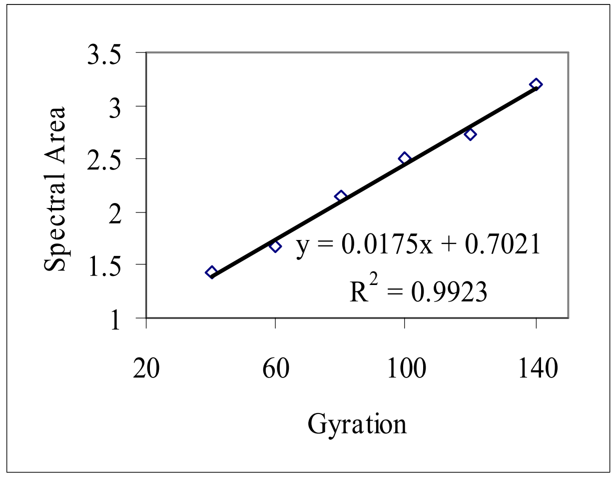

Figure 12: Spectral Area vs. gyrations

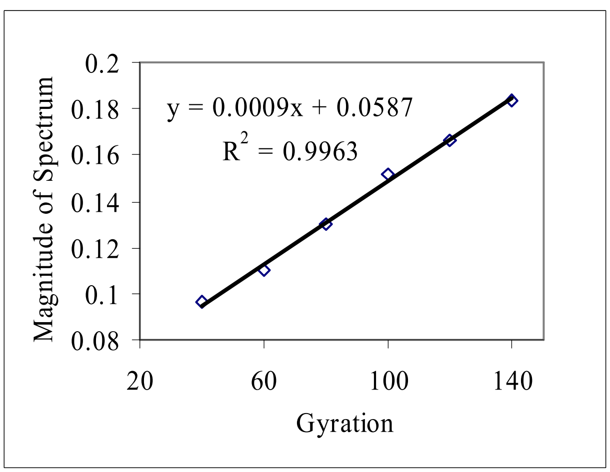

Figure 13: Magnitude of frequency spectrum vs. gyrations

4.3 Relationship between wave characteristics and the dynamic modulus

Figure 14 shows an excellent correlation between the dynamic modulus at 25 Hz and the number of gyrations. Good correlations were observed when the dynamic modulus was measured under other cyclic loading frequencies as well (10 Hz, 5 Hz, 1Hz, etc) but the results are not included in the paper. The highest correlation was observed for the dynamic modulus at 25 Hz. Consequently, the subsequent analysis was done using the dynamic modulus determined at 25 Hz. The modest correlation between the dynamic modulus and the density as seen in Figure 15 tends to support the previous observation that density measurements may not be sufficient to ensure good bonding between asphalt and aggregate to improve resistance to fatigue cracking although it may be necessary to verify void requirements.

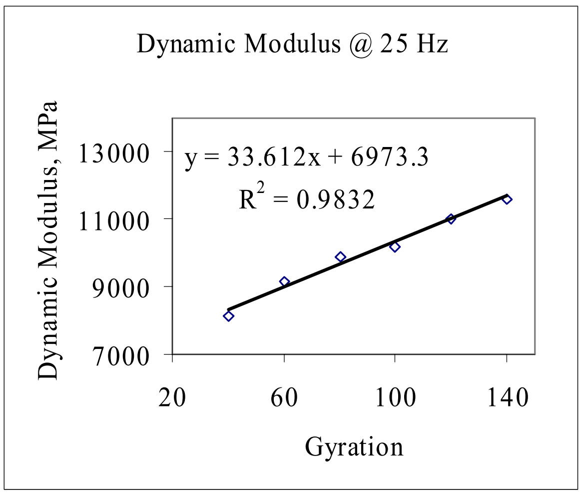

Figure 14: Dynamic modulus vs. gyration

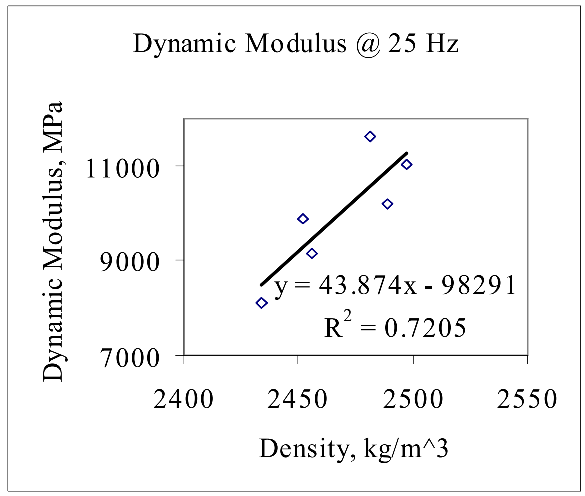

Figure 15: Dynamic modulus vs. density

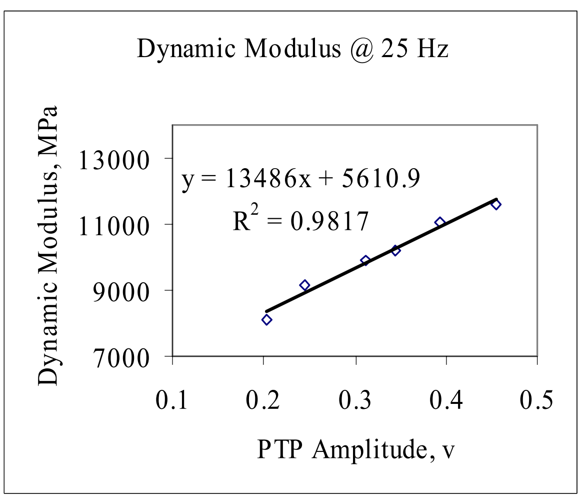

Figure 16: PTP amplitude vs. dynamic modulus

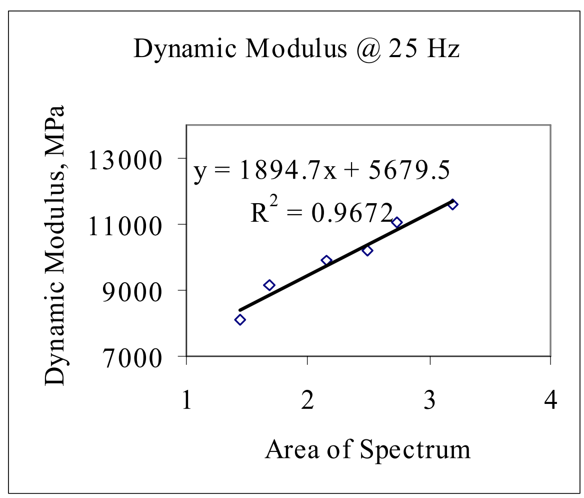

Figure 17: Spectral Area vs. dynamic modulus

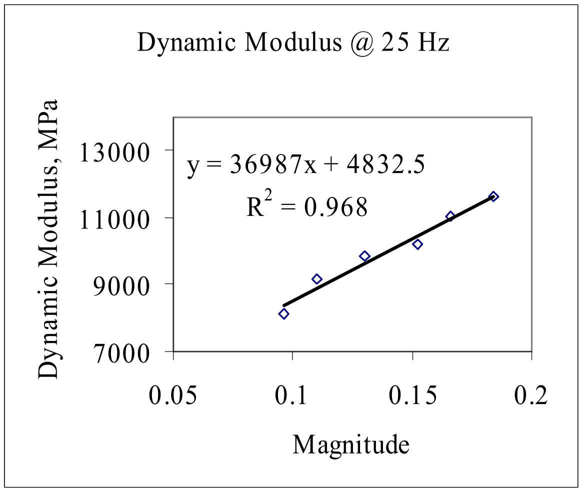

Figure 18: Magnitude of frequency vs. dynamic modulus

Figures 16-18 show the relationship between different wave characteristics and the dynamic modulus. They all showed high correlations with the dynamic modulus. Among the three parameters which showed good correlations, PTP amplitude gave the highest correlation. Any one of the three could be used as a performance indicator based on UPV testing. However, PTP amplitude would be more suitable for field testing as it can be determined readily from the oscilloscope without going through extensive mathematical computations.

5. SUMMARY AND CONCLUSIONS

The wave amplitude correlates very well with the number of gyrations while the observed correlation with density is moderate. During gyrations, the asphalt coated particles achieve greater particle to particle contact as indicated by the increase in density. In addition, the number of gyrations promotes better bonding at the aggregate-asphalt interface thereby maintaining a good continuity in the matrix. Wave attenuation is less for samples prepared with higher number of gyrations irrespective of the density which depends on the aggregate sizes present in the mix in addition to the number of gyrations. Therefore, the damping or attenuation is minimized if there is good bonding at the aggregate-asphalt interface to ensure continuous medium of travel. Traditionally, the quality of the in-place mixture is assessed in terms of density. To simulate field conditions in the laboratory, a suitable number of gyrations depending on the traffic volume are selected for mix preparation. It is expected that density increases with the number of gyrations for the mixes with similar volumetric design. However, this may not be the case always as seen in this case (Figure 8). Similar situations may arise during construction and the higher density value in some cases may not be a good indicator of good workmanship. Thus, wave characteristic such as amplitude measurements in addition to density will provide a reliable assessment of the pavement condition. The good correlation between the dynamic modulus and the wave amplitude demonstrates the potential benefit of using the wave parameters for condition assessment of in placed asphalt concrete. Future work will focus on advancing this experience and knowledge of seismic wave technology to develop a suitable NDT field testing protocol for pavement condition assessment.

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