The estimation of the dynamic Young’s (uniaxial) and shear complex moduli based upon ultrasonic measurements are presented. Phase velocities were used instead of group velocities because of the highly attenuative nature of asphalt concrete. It was observed that the dynamic moduli increase from 0 to 24 h and decrease from 24 to 36 h of oven-ageing. The modulus obtained using ultrasonic measurements is also compared with the modulus obtained using the AASHTO recommended mechanical testing procedure. The differences are due to scattering effects, which are present in ultrasonic testing and absent in mechanical testing. It was also observed that, to avoid the uncertainty associated with assuming a suitable value for the Poisson’s ratio, both the dilatational and shear velocities and corresponding attenuation measurements must be carried out. Furthermore, to eliminate the need for traditional mechanical testing during the estimation of complex moduli, frequency-dependent ultrasonic measurements must also be carried out. Results indicate that complex moduli are sensitive to the level of ageing in asphalt concrete mixtures.

Keywords: Asphalt concrete, complex modulus, dynamic modulus, oven-ageing, ultrasonic velocity, attenuation.

Introduction

Hot mix asphalt (HMA) concrete is one of the most heavily used materials in pavement infrastructure[1]. When exposed to the environment, its material properties are altered as it undergoes oxidative ageing at, or near, the top surface, which leads to pavements with graded material properties across the pavement thickness. Oxidative ageing leads to stiffening and embrittlement of the asphalt binders, which reduces the healing capacity and increases the rate of microcrack propagation. This leads pavement systems to become more prone to coalesced macrocrack formation and they may begin to develop surface-initiated fatigue cracking. In addition, the brittle pavement surface will be prone to channelling cracks, such as thermal and block cracks. Fatigue, thermal and block cracking lead to an exponential decrease in pavement serviceability and a resulting exponential increase in maintenance costs to restore the pavement condition. In a recent study by Islam and Buttlar[2], a rough pavement network was found to add an additional user cost of over $300 per vehicle per 12,000 miles driven. The encouraging news from the study was that properly timed maintenance treatments, resulting in a moderately smooth pavement over its life, yields an approximate 50-to-1 return on investment[2].

Pavement engineers face the difficult task of predicting the long-term behaviour of asphalt concrete subjected to field conditions in order to schedule preventive maintenance procedures aimed at ensuring proper pavement performance. Typically, rheology-based testing provides the foundation to understanding asphalt concrete behaviour under various conditions (for example loading, oxidative ageing, etc). These methods for evaluating existing conditions of asphalt concrete pavements are very time consuming, costly and, by themselves, may cause additional damage. As a result, decisions are often based upon visual inspection of deteriorated pavements. Furthermore, ignoring ageing- and temperature-induced property gradients in asphalt concrete pavements may yield significant errors. Complex moduli have the potential to characterise asphalt concrete subjected to field conditions. However, conventional mechanical techniques for the determination of complex moduli in asphalt concrete are also costly and time consuming. As a result, there exists the need for a quick, repeatable and less costly method for the determination of the complex moduli in asphalt concrete.

Previous studies by Velsor et al[3], Mounier et al[4] and Norambuena-Contreras et al[5] have correlated the complex modulus results obtained from ultrasonic tests to results from conventional mechanical tests; however, either the shear velocity was assumed to be constant across frequencies or the unknown Poisson’s ratio was assumed. In this study, none of these assumptions are made. Furthermore, the lack of frequency-dependent ultrasonic measurements leads to uncertainties in the construction of the master curve. When velocities are taken at multiple temperatures, they must be shifted using the time-temperature superposition as discussed by Kim[6] and Christensen[7]. If the velocity is not considered to be frequency dependent (ie only a single reported value at each temperature), the amount by which it should be shifted (ie the shift factor) is unknown. When the shift factor is unknown, comparisons must be made between the ultrasonic data and the data obtained via mechanical testing. Consequently, the need for traditional mechanical testing is not eliminated.

In Part 1 of this study, ultrasonic dilatational and shear velocities and corresponding attenuation measurements were obtained for six different asphalt concrete specimens subjected to different amounts of oven-ageing (ie 0, 12, 24, 28, 32 and 36 h of ageing). In Part 2 of this paper, using these ultrasonic measurements, the dynamic uniaxial longitudinal and shear complex moduli for a frequency range of 30 to 350 kHz are estimated, and their dependence upon oxidative ageing is discussed.

Complex moduli – basic theory and measurement techniques

Asphalt concrete is a viscoelastic material, as its material properties are dependent on both time and temperature. Accordingly, its moduli are complex. The complex Young’s (uniaxial) modulus is given by Christensen[7] as:
where:  
\[ E^* = E' + iE'' \]  
(1)

\[ E' = |E| \cos \phi \]  
(2)

\[ E'' = |E| \sin \phi \]  
(3)

\[ |E'| = \sqrt{(E')^2 + (E'')^2} = \frac{\sigma_y}{\epsilon_y} \]  
(4)

and:

\[ \tan^{-1} \left( \frac{\text{Im}(E')}{\text{Re}(E')} \right) = \tan^{-1} \left( \frac{E''}{E'} \right) \]  
(5)

Figure 1 shows a graphical representation of the complex Young's modulus. The complex shear modulus is analogous to the uniaxial modulus by simply substituting the uniaxial modulus parameters for the shear moduli parameters \( G^* \), \( G' \), \( G'' \) and \( |G^*| \) in the above equations.

\[ \text{Figure 1. Graphical representation of complex Young's modulus.} \]

**Mechanical complex modulus test**

Conventional techniques for measuring the dynamic modulus of asphalt concrete involve mechanical tests such as the compressive dynamic modulus test and the indirect tension test, as described by Kim[11]. Here, the focus will be on the compressive dynamic modulus test. The American Association of State Highway and Transportation Officials (AASHTO) standard[13] AASHTO T 342-11 details the compressive dynamic modulus test procedures for determining the dynamic modulus and phase angle of asphalt concrete over a range of frequencies and temperatures. The set-up consists of a servo-hydraulic loading frame with the capability of applying a sinusoidal compressive loading at a specified frequency (for the range of 0.1 to 25 Hz). The system contains an environmental chamber, which is used to control the temperature of the asphalt concrete specimen during testing. The specimen consists of a core extracted from a cylindrical gyratory compacted specimen (150 mm tall, 102 ±2 mm diameter). Four linear variable differential transformers (LVDT) are placed at four locations around the circumference of the HMA specimen (90° apart) to measure the average axial deformation. A load cell measures the applied load. The master curve is constructed by performing tests at temperatures of –10, 4.4, 21.1, 37.8 and 54°C for sinusoidal loading at frequencies of 0.1, 0.5, 1.0, 5, 10 and 25 Hz for each temperature.

\[ E^* = \rho \left( \frac{c_s}{c_L} \right)^2 \left( \frac{\alpha (c_s)}{c_L} \right)^2 \]  
(6)

where \( \rho \) is the material density. The complex shear modulus \( G^* \) can be written as follows:

\[ G^* = \rho \left( \frac{c_s}{c_L} \right)^2 \]  
(7)

and the complex Poisson’s ratio is given by:

\[ \nu^* = \frac{1 - 2 \left( \frac{c_s}{c_L} \right)^2}{2 \left( \frac{c_s}{c_L} \right)^2} \]  
(8)

**Experimental results**

The real components of the ultrasonic dilatational and shear phase velocities and their corresponding attenuations were measured experimentally and presented in Part 1 of this study. In this paper, its meaning when there is high attenuation as the ‘wave packet' does not maintain its shape. The Poisson’s ratio is a function of the shear to dilatational complex velocity ratio. Thus, to obtain the complex moduli, it is necessary to have the dilatational ultrasonic parameters (ie dilatational velocity and attenuation measurements) and either the Poisson’s ratio or the shear ultrasonic parameters (ie shear velocity and attenuation measurements).

The elastic viscoelastic correspondence principle, as discussed by Christensen[14], makes it possible to use complex material properties in the solution of the elastic wave equation, see Kinsler et al[15]. Following Christensen[14] and Kinsler et al[15], the one-dimensional complex wave equation is written as:

\[ \frac{d^2 u}{dt^2} = \frac{1}{c^2} \frac{d u}{dt} \]  
(9)
these ultrasonic velocities and attenuation measurements are used to determine the complex moduli. Furthermore, comparisons are also made between the complex moduli obtained via the ultrasonic technique and the conventional mechanical approach as recommended by the American Association of State Highway and Transportation Officials (AASHTO).

Using the ultrasonic velocity and attenuation data obtained in Part 1 of this study, Figure 2 shows the dynamic uniaxial modulus $|E^*|$ and the dynamic shear modulus $|G^*|$ as a function of frequency for different amounts of ageing of the asphalt concrete test samples. From this point forward, the dynamic modulus will be called $|E^*|_{\text{specimen}}$, where the subscript denotes the specimen according to the amount of ageing to which it was subjected. As the frequency increases, $|E^*|$ increases for all specimens. For example, for the frequency range of 30 to 350 kHz, $|E^*|_{\text{specimen}}$ increases from $\approx 5$ to $\approx 28$ GPa. This increase in $|E^*|_{\text{specimen}}$ is greater than what would be obtained from a corresponding mechanical test. This discrepancy can be attributed to scattering energy losses, which are absent in the AASHTO recommended mechanical test procedure.

As expected, $|E^*|$ follows the same trend as the velocities with respect to the amount of ageing: $|E^*|$ increases from 0 to 24 h and decreases from 24 to 36 h of oven-ageing time. Although the binder becomes stiffer as it ages, it also loses adhesion properties, which leads to a decrease in bonding between the mastic and aggregates, and to weaker bonds between the fines and the binder in the mastic. After 24 h of ageing, this phenomenon results in a decrease of the overall composite (asphalt concrete mixture) stiffness. The complex shear modulus $G^*$ follows similar trends to $E^*$.

The phase angle decreases with increasing frequency for all specimens, see Figure 3. Typically, the same trend is also observed in mechanical testing; however, discrepancies still exist. In mechanical testing, the phase angle is larger at lower frequencies and approaches zero with increasing frequencies. Via ultrasonic testing, the phase angle decreases with increasing frequencies; however, it seems to reach an asymptote at approximately 14°. This asymptote is likely to be caused by the scattering energy losses at higher frequencies. There is no discernible trend with respect to ageing.

![Figure 3. Phase angle (degrees) as a function of frequency for specimens subjected to various amounts of oven-ageing (0 to 36 h) ](image)

Figure 4 contains the complex Poisson’s ratio as a function of frequency. The real component of the Poisson’s ratio decreases with increasing frequency. The imaginary component decreases with increasing frequency from 30 to 190 kHz; above 190 kHz it increases with increasing frequency.

**Comparison with mechanical tests**

Figure 5(a) shows the dynamic modulus $|E^*|$ obtained using both the conventional mechanical testing method and the ultrasonic method. In Figure 5(a), only the raw ultrasonic data was used during the estimation of the dynamic modulus using the ultrasonic approach. Figure 5(a) shows that the complex modulus obtained via the ultrasonic approach does not fully coincide with the modulus obtained using the conventional mechanical tests. The observed differences are mainly a consequence of the ultrasonic velocities and attenuation measurements being affected by ultrasonic scattering at relatively higher frequencies, while scattering does not affect the results when conventional mechanical tests are used to evaluate $|E^*|$. The presence of wave scattering causes some differences because of the following two reasons: (1) scattering increases the measured attenuation with frequency; and (2) the measured shear velocity is dependent upon frequency, which corresponds to a change in the Poisson’s ratio. If scattering effects were not present during ultrasonic wave propagation, the attenuation would be lower and the shear velocity would not be frequency dependent, which would lead to a nearly constant Poisson’s ratio. As a result, lowering the attenuation and forcing the Poisson’s ratio to be constant (i.e., forcing the shear velocity to be constant) should allow
for the two methods to coincide.

Figure 5(b) is included to illustrate some of the traditional (and possibly unwarranted) assumptions encountered in the literature. Figure 5(b) shows the mechanical data along with the ultrasonic data, with the following major assumptions: (1) the attenuation is arbitrarily decreased by 20 Np/m; and (2) the shear velocity is forced to remain constant. Based on scattering effects, it might be possible to characterise how much the attenuation should be shifted. It is observed that attenuation does not play a significant role in the determination of these curves because the complex velocity is a function of the attenuation normalised by the angular frequency $\alpha(\omega)$ (see Equation 8). Thus, for high frequencies (ie the ultrasonic range), this ratio is a small number. However, the uncertainty with the second assumption arises in choosing a proper value for the shear velocity, which, empirically, varies with frequency. Since the dilatational velocities are nearly constant, the second assumption corresponds to a constant Poisson’s ratio. Figure 6 shows the relationship between the Poisson’s ratio and shear velocity for a constant dilatational velocity (mean of higher frequencies), ie selecting a constant shear velocity is equivalent to selecting a constant Poisson’s ratio. Figure 5(b) shows the ultrasonic results with an arbitrary reduction in attenuation of 20 Np/m for multiple assumptions of the shear velocity (within the measured range), see Figure 6.

The phase angle measured via the ultrasonic approach is higher

Figure 5. The dynamic modulus $|E'|$ (GPa) obtained via conventional mechanical testing (grey dashed line) compared with the $|E'|$ obtained via the ultrasonic method based on: (a) no assumptions made; and (b) the Poisson’s ratio, $\nu$, is assumed to be constant and an arbitrary decrease in attenuation of 20 Np/m is assumed for both the dilatational and shear waves.

Figure 6. The mean Poisson’s ratio as a function of shear velocity in unaged specimen for frequencies above 100 kHz (where the dilatational velocity is relatively independent from frequency)
than the phase angle obtained using the traditional mechanical testing, mainly because of the ultrasonic wave scattering. For the same reasons, the Poisson’s ratio, which is a function of the complex dilatational and shear velocities, exhibits similar discrepancies due to scattering.

Construction of the master curve

Previous studies, Velsor et al., Mounier et al. and Norambuena-Contreras et al., have measured the group velocity at different temperatures without considering frequency dependency; thus, the velocity at each temperature was a discrete value. When constructing the master curve, it is necessary to shift the data using the time-temperature superposition (TTS). Shifting the data, however, requires that the shift factor be known. If velocity measurements are not taken with respect to frequency, then the only way to obtain the shift factor is by comparing it to a known master curve, ie a model fitted to data obtained via conventional mechanical testing. Consequently, the need for mechanical testing is not eliminated. To construct the master curve based solely upon ultrasonic data, both velocities and the corresponding attenuations must be known with respect to a range of frequencies.

Correlation with other tests

In a comparison of the results of all the tests presented, it is observed that all the test results reach a peak (or trough) at some level of oven-ageing time. Until it reaches this critical ageing time, the structural response (for example stiffness) typically increases with ageing, after which it decreases. The amount of ageing at which these peaks (or troughs) occur varies slightly between tests. Based on the results from the ultrasonic and acoustic emission tests, this threshold appears to be around 24 h of oven-ageing for this mixture. For example, as the amount of ageing increases, both the ultrasonic dilatational and shear velocities increase until 24 h of ageing, after which they decrease with increasing ageing. The magnitude of the ultrasonic attenuation follows a comparable trend, where it decreases from 0 to 24 h, after which it increases with increasing ageing. The rate of change of the embrittlement temperatures (obtained using AE), with respect to ageing time, increases relatively slowly until 24 h of ageing, after which it rapidly increases; see Part 1 of this study. This response of asphalt concrete with ageing is also supported by the results using the disc-shaped compact tension (DC(T)) fracture energy tests. Published data using the DC(T) tests also indicates that the fracture energy increases up to a critical ageing time (~10 h of oven-ageing), after which it decreases; see Figure 14 in Part 1 of this study.

Conclusions

Complex moduli were calculated for asphalt concrete specimens subjected to various amounts of oven-ageing time (0, 12, 24, 28, 32 and 36 h) using the ultrasonic velocity and attenuation measurements presented in Part 1 of this study. The complex moduli calculated via ultrasonic testing are compared with the complex moduli obtained via conventional mechanical testing. The discrepancies observed between the two methods are due to the scattering effects, which exist in ultrasonic wave propagation and are absent in mechanical testing. It is observed that to avoid the uncertainty of ‘assuming’ the value of the Poisson’s ratio, both ultrasonic dilatational and shear velocities and the corresponding attenuation measurements need to be obtained as a function of frequency. It is also noted that frequency-dependent ultrasonic measurements must be made to calculate frequency-dependent complex moduli, otherwise the need for the conventional mechanical testing to estimate the complex moduli is not eliminated.

The correlation between the complex moduli and the amount of ageing suggests that this non-destructive method can be successfully employed to evaluate the effects of oxidative ageing in asphalt concrete. It was observed that, across all frequencies, the dynamic modulus increases from 0 to 24 h and decreases from 24 to 36 h of oven-ageing. From this trend, it can be concluded that after 24 h, the binder’s increase in stiffness with ageing and its decrease in adhesive properties, which leads to debonding between the mastic and the aggregates and to bond deterioration among the fines in the mastic, results in an overall decrease in the dynamic modulus of the overall mixture. Results from the ultrasonic complex moduli are consistent with results obtained using DC(T) fracture energy tests and with AE-based embrittlement temperatures obtained during cooling from room temperature to –50ºC. Therefore, an acoustic-based approach has the potential to be used as a pavement field inspection/monitoring tool. First, evaluation/characterisation of asphalt concrete properties and their gradation through the pavement thickness could be made using extracted field cores. In the end, embedded wireless sensor nodes could be used to monitor the pavement response to the environment without core extraction.

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