Innovative Non Destructive Test Method for Condition Assessment of Longitudinal Joints in Asphalt Pavements

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ABSTRACT
Poor-quality longitudinal construction joints often contribute to the poor performance of hot mix asphalt pavements. Previously, destructive and time consuming methods were used to assess longitudinal joints. The nuclear gauge is currently used to measure density to ensure good compaction but it is not used to assess the quality of longitudinal joints. The joint quality depends not only on the compaction but also on the bond strength among particles. Therefore, an innovative non-destructive technique has been developed; which is based on the use of ultrasonic surface waves. The sensitivity of different signal processing techniques to detect changes in the condition of longitudinal joints was studied in detail. The results revealed that the new transmission wavelet coefficient (WTC) is a promising technique for the non-destructive evaluation of asphalt pavements. Field tests on three different highway sections (deteriorated, new echelon paved, and new conventionally paved joints) showed WTC values less than 15%, between 50% and 61 %, and, higher than 100% for deteriorated, conventional, and echelon paved joints, respectively.

Resumen
La mala calidad de juntas longitudinales de construcción a menudo contribuye al mal desempeño de pavimentos asfalticos de mezcla caliente. Anteriormente, métodos destructivos y lentos se utilizaron para evaluar las juntas longitudinales. La prueba nuclear se utiliza actualmente para medir la densidad y asegurar una buena compactación, pero no se utiliza para evaluar la calidad de las juntas. La calidad de la junta no sólo depende de la compactación, sino también en la fuerza de adhesión entre las partículas. Por lo tanto, una nueva técnica no-destructiva se ha desarrollado, la cual utiliza las ondas de ultrasonido de superficie. La sensibilidad de varias técnicas de procesamiento de señales a cambios en el estado de las juntas longitudinales se estudió en detalle. Los resultados revelaron que el nuevo coeficiente de transmisión wavelet (WTC) es una técnica prometedora para la evaluación no destructiva de los pavimentos de asfalto. Pruebas de campo en tres secciones de una autopista (deteriorada, de construcción convencional, y nuevas de construcción escalonada) mostraron valores de WTC inferiores al 15%, entre 50% y 61%, y superior al 100% para las juntas deterioradas, de construcción convencional, de construcción escalonada, respectivamente.

1 INTRODUCTION

Poor-quality longitudinal construction joints often contribute to the poor performance of hot mix asphalt (HMA) pavements. In the past, the longitudinal construction joints were evaluated in terms of the in-place density measurements obtained through coring at five different locations across the joint (Foster et al. 1964, Finn and Epps 1980). This approach was destructive and time consuming. Secondly, density measurements are not sufficient to assess the bond strength between two surfaces which ensures good quality longitudinal constructions joints in asphalt pavements. To address this problem, an innovative non destructive technique for condition assessment of the longitudinal construction joints in asphalt pavements has been developed at the University of Waterloo. This method involves laboratory and field investigations using surface waves to assess the relative condition of the longitudinal joints in comparison to the condition of the adjacent good quality joint-free asphalt pavement surface built according to the specification. The proposed wave-based testing techniques not only reduce the damage associated with coring, but also provide a uniform condition assessment of the longitudinal joints.

2 THEORETICAL BACKGROUND

A surface impact simultaneously generates surface waves and body waves in all directions. If surface defects or boundaries exists, some surface and body waves will be reflected and reach the receivers either directly from the source or through reflections from the bottom of the surface layer. All these waves interfere with the direct surface waves, thus leading to fluctuations or abrupt changes in the phase velocity profile and the dispersion curve as well (Jones 1962 and Vidale 1964).

Waves with various frequencies are transmitted to the medium by a mechanical impact (e.g. an impulsive hammer or a transmitter) on the ground surface. The propagation of the waves is monitored by an array of receivers on the surface. The receiver spacing depends on several factors: the wave velocity in the test medium, the expected investigation depth, the frequency range used; the attenuation properties of the medium, and the instrumental sensitivity (Nazarian et al. 1983). In general, short receiver spacing is used for shallow measurement, while long spacing is used for deep measurement. In addition, seismic waves must travel a minimum distance from the source before becoming well formed (near-field effects). Conversely, low signal-to-noise ratios can be present at large distances from the source, relative to the wavelength (far-field effects). A number of criteria that relate receiver spacing to wavelength has been proposed (Lysmer 1965 and Sheu et al. 1988).

2.1 Analysis of Seismic Waves

The propagation characteristics of surface waves and body waves are a function of the elastic properties and fracture patterns of the medium. Thus, changes in wave characteristics (e.g. velocity and attenuation) reflect changes in the medium. Signal detected by the receivers are processed using different techniques for subsequent analysis as described later.

Figures 1 shows an example of the full signal received at the 90 mm spacing (the spacing between the source and the second plate where the receiver is placed), using 50 kHz P-wave transducer, from the field testing on an asphalt pavement. The captured wave forms (full signals) contain several wave components including body waves (P-waves), surface waves (R-waves) and other reflected waves from the bottom surface or any other boundaries. P-waves travel faster than R-waves and thus appear before the arrival of R-waves. Thus, P-waves are detected by the first arrival and R-waves are by the second arrival. For the purpose of condition evaluation, the wave attenuation parameters corresponding to the full signal, P-wave portion and R-wave portion are usually examined. Identifying the correct wave type is critical for accurate assessment of the wave attenuation caused by flaws present in the material.

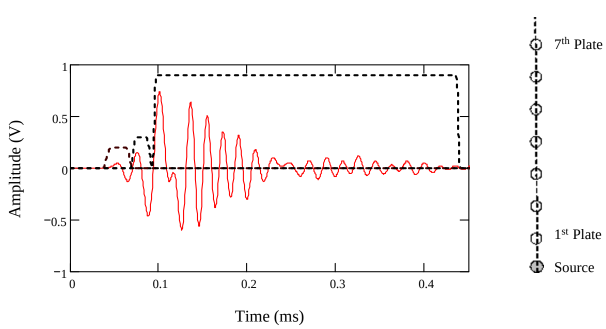

Figure 1. Full signal received at 90mm from field testing (Jiang 2007)

2.2 Mechanisms of Wave Attenuation

When waves travel through a medium, its energy or intensity diminishes with distance. The wave amplitude is reduced because of two basic mechanisms: scattering and absorption. Scattering is the reflection of the wave in random directions (Krautkrämer and Krautkrämer 1990). Absorption is the conversion of the mechanical energy into heat because of the inter-particle friction. The combined effect of scattering and absorption produces wave attenuation. Therefore, ultrasonic attenuation represents the decay rate of the wave as it propagates through the material. Attenuation often serves as a measurement tool to quantify the change in wave amplitude as a result of scattering and absorption. The amplitude change of a decaying wave can be expressed as:

$$A(x) = A_0 e^{-\alpha x} \qquad [1]$$

where, 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 α which depends on the type of material. The attenuation coefficient increases with frequency, thus high frequencies (small wavelengths) attenuate faster than low frequencies. Thus, by keeping the travel distance constant, the wave attenuation corresponding to the different medium through which the waves travel could be used for comparative evaluation of the medium.

In this study, the wave attenuation associated with joints will be compared to wave attenuation corresponding to the joint-free surface for comparative condition assessment of the joint.

2.3 Fourier Transmission Coefficient (FTC)

Every signal can be visualized as a summation of sine and cosine waves with appropriate amplitudes and phases by using the Fourier transform (Qian 2002). The Fourier transform (X(f)) of a signal (x(t)) is expressed as:

$$X(f) = \int_{-\infty}^{\infty} x(t) \cdot e^{-j \cdot 2\pi f \cdot t} dt \qquad [2]$$

where f is frequency, t is time, and j denotes the imaginary component of complex numbers.

Fourier transmission coefficient (FTC) methods have been used effectively to measure the depth of surface-breaking cracks (Popovics et al. 2000, Song et al. 2003 and Yang et al. 2006). An equal-spacing FTC method was studied in the University of Waterloo for condition assessment of longitudinal joints in asphalt pavements. This method is based on experimental study where two receivers are placed at equal distances from the source. The equal spacing configuration is achieved by placing the source and receivers at four corners of a square array, as shown in Figure 2, so that the two sides of the square run parallel to the joint (joint-free surface) while the other are perpendicular to the joint.

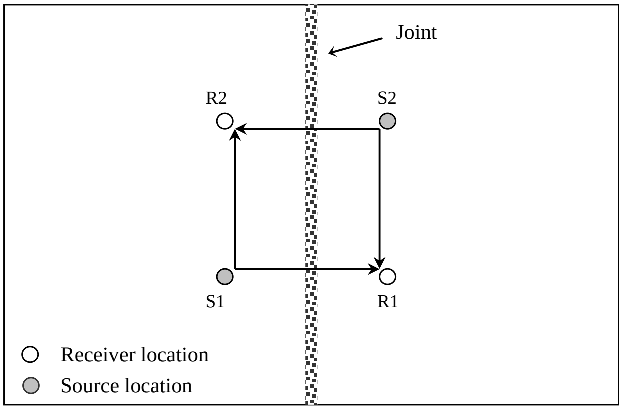

Figure 2. Testing geometry for equal-spacing transmission coefficient method (Jiang 2007).

To assess the relative strength of the joint, the wave attenuation was measured across the joint as well as along the joint-free surface. The signals detected by the receiver are represented in the frequency domain in terms of a simple product function of wave signal impact caused by the source, receiver and the medium as follows:

$$F_{S1\_R1}=S_{S1}\cdot M_{S1\_R1}\cdot R_{R1} \qquad [3]$$

where, F_{S1_R1} is the Fourier transform in frequency domain of the time signals f_{S1_R1}; S_{S1} is the variation due to the source response term including the coupling effect at location S1; M_{S1_R1} is the wave transfer function of the medium between locations S1 and R1; R_{R1} is the variation caused by the receiver response term including the coupling effect at location R1.

Likewise, the other time three time signals from the source-receiver locations from S2 to R1, S1 to R2 and S2 to R2 are expressed as:

$$F_{S2\_R1} = S_{S2}\cdot M_{S2\_R1}\cdot R_{R1} \qquad [4]$$

$$F_{S1\_R2} = S_{S1}\cdot M_{S1\_R2}\cdot R_{R2} \qquad [5]$$

$$F_{S2\_R2} = S_{S2}\cdot M_{S2\_R2}\cdot R_{R2} \qquad [6]$$

Using the relationship given by the Equations 3 to 6 the amplitude ratio (FTC) between the signal across the joint and the signal through the joint-free surface is computed using the following equation.

$$FTC = \sqrt{\frac{F_{S1\_R1}\cdot F_{S2\_R2}}{F_{S1\_R2}\cdot F_{S2\_R1}}} = \sqrt{\frac{M_{S1\_R1}\cdot M_{S2\_R2}}{M_{S1\_R2}\cdot M_{S2\_R1}}} \qquad [7]$$

Accordingly, FTC permits elimination of the variations associated with unknown characteristics of the receiver, the wave source and the coupling while assessing the condition of surface defects.

2.4 Wavelet Transmission Coefficient (WTC)

The WTC can be considered an improvement to the FTC in signal processing. This method eliminates the bias associated with windowing of P-waves and R-waves involved in the FTC analysis. The wavelet transform compares the similarities between the time signal and a window of variable size as it is time shifted along the signal. This process provides the frequency domain representation of the windowed signal.

The wavelet transform is computed in discrete form, given by:

$$W_{k,m} = \frac{1}{\sqrt{k}}\sum_{n=0}^{N-1} x_n \cdot \psi^*\left(\frac{n-m}{k}\right) \qquad [8]$$

where x_n represents the discrete-time signal over a time period given by $N\cdot\Delta t$, N is the total number of sampled points of the time domain signal, Δt is the time sampling interval, $\psi(n)$ represents the window known as mother wavelet, the star (*) denotes the complex conjugate, k is an integer counter giving the center frequency of the wavelet $f_0 = \frac{1}{2k\,\Delta t}$, and m is an integer counter giving a shift time $m\cdot\Delta t$.

Similar to the FTC, WTC based on wavelet transform is computed as follows:

$$WTC = \sqrt{\frac{W_{S1\_R1}\cdot W_{S2\_R2}}{W_{S1\_R2}\cdot W_{S2\_R1}}} \qquad [9]$$

where, the four constants W_{S1_R1}, W_{S1_R2}, W_{S2_R1} and W_{S2_R2} are the peak amplitudes of the wavelet transforms of the four signals f_{S1_R1}, f_{S1_R2}, f_{S2_R1} and f_{S2_R2} respectively.

In ideal situations where the medium is intact and uniform, there is a total transmission of energy and the WTC = 1. For defective surface, it will be less than 1. In other words, the value of WTC falls between 0 (complete attenuation) and 1 (complete transmission). However, in some cases, it is not unusual to get WTC >1 particularly for non homogeneous materials in good condition such as new asphalt pavements built using good construction techniques. This means that the surface, in question, is in better condition than the surface used as reference for comparison because of the inherent variability within the heterogeneous materials. In such cases, the tested surface is considered in excellent condition.

3 LABORATORY INVESTIGATION

The laboratory investigation was carried out to examine the suitability of using different signal processing techniques such as the FTC and WTC for assessing the condition of the joints between two asphalt pavement surfaces. The sensitivity of the wave attenuation parameters to identify different types of joints was examined by testing three different joint conditions built in three slabs using a trial error process. Jointed rectangular asphalt concrete slabs (800 mm x 600 mm x 80 mm) with different construction joint conditions were fabricated in the laboratory using a wooden molding frame. Having evaluated different compaction techniques, the traditional laboratory method of compaction using a hand-held hammer (7 kg) with a tamping foot of 200 mm x 200 mm dimension was used for the preparation of the slabs. For each slab, the asphalt concrete materials were compacted in two lifts with each 40 mm thick. During the compaction, the numbers of blows were varied to produce variable densities near the joints to simulate good to poorly constructed joints. A detailed description of the procedures used for the slab preparation is provided in reference (Jiang 2007). The joint conditions were described subjectively as fair, weak and poor proportionally to the level of compacting effort used near the joint. It was difficult to achieve a good joint condition in the laboratory using the hand-held hammer technique. However, the jointed slabs were considered suitable to evaluate different NDT techniques for field evaluation.

Laboratory tests were carried out using the procedures described in sections 2.3 and 2.4. To improve the coupling between the surface and the source/receivers, thin 10 mm diameter steel plates were epoxied to the slab surface. The signals were collected in a laptop computer for signal processing. The results showed that the FTC and WTC parameters were able to differentiate between the fair (Slab 1), week (Slab 2) and poor (Slab 3) construction joints built in the laboratory as illustrated in Figure 3. The FTC and WTC values less than 1 indicate that wave attenuation has occurred across the joint. The results further indicated that the evaluation based on the FTC and WTC were consistent indicating that both parameters are suitable for condition assessment of longitudinal joints in asphalt pavements. However, additional data analysis of P-waves and R-waves revealed that the FTC signal processing technique based on time windowing can be affected by wave interference in some cases which can lead to biased windowing and misleading conclusion. Therefore, it was concluded that the WTC is more suitable for use as a condition index because it does not require time windowing. As a follow up work, a filed study was conducted to validate the findings of the laboratory investigation as described in the following section.

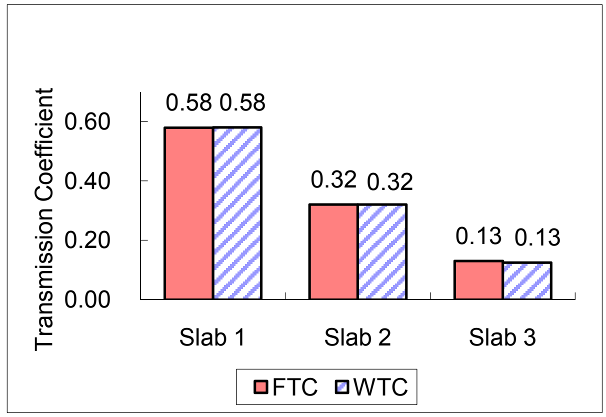

Figure 3. Condition assessment of joints in the slabs prepared in the laboratory

4 NDT METHODS USED FOR FIELD EVALUATION

Field tests were carried out in 2007 on Hwy 401 using the procedures described above. To improve the coupling between the surface and the source/receivers, thin 10 mm diameter steel plates were epoxied to the pavement surface, as shown in Figure 4. The condition assessment in the field was done using two types of tests: 1) ultrasonic testing and 2) impact hammer testing. First test method involves the use of high frequency waves electrically generated through a 50 kHz P-wave transmitter. High frequency waves are suitable for assessing the condition of shallow pavement layers up to 50 mm deep in a narrow area of 100 mm x 100 mm length. The second method involves the use low frequency waves (<15 kHz) generated by a specially designed impact hammer (Dytran). This is suitable for a full depth investigation of up to 650 mm depending on the frequency selected and will cover an area of approximately 300 mm x 300 mm. Table 1 summarized properties of the sources and receivers used in the field tests.

Table 1. Properties of the sources and receivers used in the field tests on Hwy 401.

Test Method	Source	Receiver
Ultrasonic	Pundit P-wave transducer, Narrow frequency band, resonant frequency = 50 kHz, diameter = 50 mm, mass = 490 g	Accelerometer, PCB353A65, 10% flat frequency response over 1-25 kHz, resonant frequency > 40 kHz, sensitivity = 100 mV/g, mass = 2.1 g, diameter = 8.3 mm
Impulse Hammer	Dytran Multi-range Impulse Hammer, 5850B, Upper Limit of Frequency Range = 75 kHz, Max force = 35 kN, BNC connector, 3 sensitivity levels 0.22, 0.022, and 0.0022 mV/g, Hammer mass = 275 g, head mass = 150g	Dytran Accelerometer, 3056A3, 10% flat frequency response over 1-10 kHz, resonant frequency = 30 kHz, sensitivity = 500 mV/g, mass = 10 g, diameter = 12.7 mm

Same signal processing and analysis techniques were used for both tests. However, the spacing between the source and the receiver used in the two tests is different. The spacing between the source and the receiver was selected for each test method in such a way that a clearly defined signal is received.

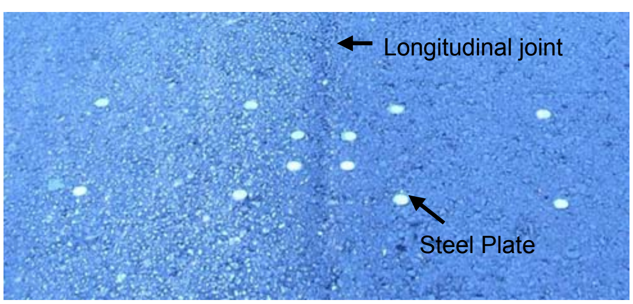

Figure 4. Steel plates installed across the joint for testing on Hwy 401

These field tests involved the evaluation of existing deteriorated joints, new echelon paved and new conventionally paved joints, as shown in Figure 5. The UPV test results in Figures 6 and 7 showed that the transmission coefficients (FTC and WTC) for deteriorated joints are less than 15%. For conventional joints, the transmission coefficients are between 50% and 61%, and for echelon paving, the transmission coefficients are greater than 100%.

Figure 5. NDT testing of longitudinal joints using seismic waves on Hwy 401

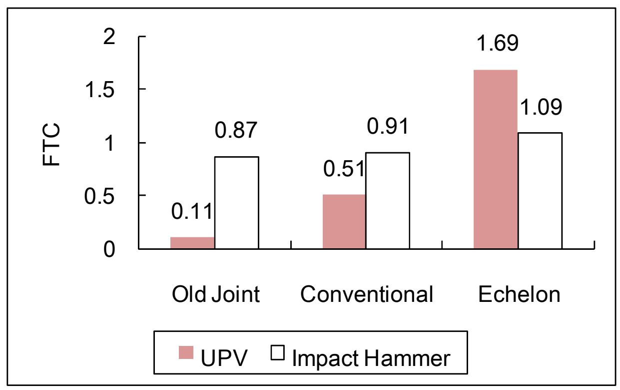

Figure 6. FTC test results - Hwy 401

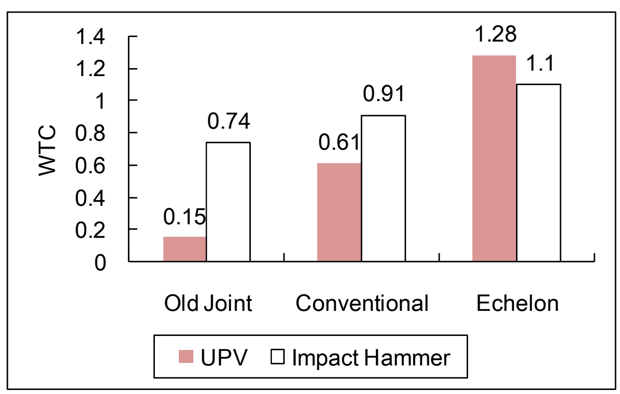

Figure 7. WTC test results - Hwy 401

The hammer test results show the same trend but higher transmission coefficients, for old and conventional joints. The likely reason for the high transmission coefficient ratio is that impact hammer tests provide the average assessment of the joint condition across the full depth of up to 650 mm while the UPV test captures only the top 50 mm joint depth. The transmission coefficients of less than 15% from the UPV test for poor joint indicates that the joint was badly deteriorated at the top 50 mm deep cracked joint in comparison to the overall depth of the joint. This is reasonable because the most of the joint deterioration starts from the surface and extends towards the bottom.

The difference between the ultrasonic test and the hammer test is noticeable but not considered significant. The ultrasonic test involves the use of higher frequency in comparison to the hammer test and thus the ultrasonic test is expected to be more sensitive to flaws. Studies have demonstrated that low frequency measurements are insensitive to flaws that are smaller than the signal wavelength (Krautkrämer and Krautkrämer 1990).

5 SUMMARY AND CONCLUSION

A research study was carried out to develop a suitable NDT method based on seismic wave technology for condition assessment of longitudinal joints in asphalt pavements. The scope of the work included literature review, laboratory investigation and a field study. The practical application of this study is an efficient and cost-effective non-destructive method for the condition assessment of longitudinal joints in the field. The results of this study show that the NDT method based on seismic wave technology has the potential for application in the field to ensure the construction of good quality pavements. More specifically, the findings of this study are summarized as follows:

- The wave-based technique is suitable to assess the condition of the joint.
- WTC is considered to be the most suitable parameter for field assessment.
- The ultrasonic test will be suitable for testing the conditions of joints up to 50 mm depth
- The impact hammer generates long waves that are not sensitive enough for evaluation of a joint in a 50mm thin asphalt pavement, but it can be used for general characterization of a pavement structure up to 650mm deep.
- The field test clearly identified the deteriorated joints from the newly constructed joints. As well the test is sensitive enough to distinguish between the joints constructed using the conventional method and the echelon paving method.

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