Field Condition Assessment of Longitudinal Joints in Asphalt Pavements Using Seismic Wave Technology

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ABSTRACT
Poor-quality longitudinal construction joints often contribute to the poor performance of hot mix asphalt (HMA) pavements. Traditionally, the longitudinal construction joints are evaluated in terms of in-situ density measurements obtained through coring at five different locations across the joint. This approach is destructive, time consuming which limits the implementation of the quality assurance and quality control (QA/QC) plan to ensure the construction of good quality longitudinal joints in asphalt pavements. To address this problem, an innovative non destructive technique (NDT) for condition assessment of the longitudinal construction joints in asphalt pavements has been developed at the University of Waterloo in collaboration with the Ministry of Transportation, Ontario. This method involves the use of ultrasonic 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. In this approach, novel experimental and signal processing techniques are used to minimize the variability associated with unknown limitations of wave source and receivers, wave path characteristics, and the effects of source/receiver coupling used for measuring wave attenuation across the joints. Based on the findings of the laboratory study, a field testing protocol was developed involving two types of NDT tests. A pilot field study was conducted to evaluate the suitability of the test protocol developed for field applications. Presented in this paper are the results of the pilot study which indicates that the proposed NDT test method is a viable and effective alternative to density measurements for field assessment of the longitudinal joints in asphalt pavements.

1 INTRODUCTION

Traditionally, in-situ density of asphalt concrete is used as a good performance indicator of the construction of longitudinal joints. This evaluation is done by comparing the in-place density obtained through pavement cores at five locations across the longitudinal joint of the pavement typically at the centerline, and at locations 150 mm, and 450 mm on either side of the centerline (*1*, *2*). This is based on the premise that density measurements will reflect the degree of compaction achieved near and at the joints between adjacent and paving lanes. Good compaction near the joints is expected to provide good bonding between adjacent lanes leading to good performance. However, current density measurements are destructive and time consuming. Recognizing this limitation, the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo initiated a research project in 2005 jointly with the Ministry of Transportation, Ontario (MTO) to develop a suitable non-destructive test (NDT) for evaluating the quality of longitudinal construction joints of asphalt pavements. NDT method is expected to reduce the number of cores required and provide a more uniform condition assessment of the longitudinal joints.

As part of this initiative, an experimental work was carried out to study (Phase I study) the correlation between wave parameters and the quality of hot mix asphalt (HMA) mix. In the Phase I study, a non-destructive Ultrasonic Pulse Velocity (UPV) test using seismic waves has been successfully used to establish a high correlation (R square >0.9) between the wave characteristics and the degree of compaction achieved (*3*). This strong correlation indicates that UPV technique can be used to evaluate the quality of longitudinal construction joints in asphalt pavement as the joint quality depends on the paving operation and the percent compaction achieved near the joint to establish good contacts at the interface between two adjacent and parallel HMA mats. Consequently, the next phase of the study (Phase II) was conducted to examine the effectiveness of using the wave characteristics to assess the condition of longitudinal joints and to develop a suitable NDT testing protocol for condition assessment of longitudinal joints in the field.

2 OBJECTIVE AND SCOPE OF THE STUDY

The objective of the Phase II study was two fold: first, to select a signal processing and analysis technique suitable for capturing wave signals transmitted through pavement layers and to measure the wave attenuation parameters identified in Phase I study. Second, to develop a suitable a testing protocol for the assessment of longitudinal asphalt pavement construction joint conditions in the field. The scope of the work includes; a) preparation of asphalt slabs (with construction joints) and ultrasonic testing of the pavement slabs in the laboratory, b) a preliminary field trial experiment at the CPATT test site, and c) a follow up pilot field study on one of the major highways in Ontario to examine the effectiveness of using the testing protocols developed for condition assessment of construction joints in asphalt pavement.

3 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 *(4,5)*.

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 (*6*). 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 (e.g. *7*, *8*). One commonly accepted is expressed as (*9*):

$$\frac{\lambda_R}{3} < x < 2\lambda_R \tag{1}$$

where λ_R denotes wavelength of R-wave, and *x* represents the receiver spacing that is commonly selected as equal to the distance between the source and the first receiver.

3.1 Analysis of Seismic Waves

Approximately 33 percent of the impact energy propagates as body waves and the remaining 67% impact energy propagates as surface waves or R waves near the surface of the semi-infinite medium. Body waves have two components: compression waves or P-waves (26%) and shear waves or S waves (7%). The body waves propagate spherically into the body of the medium. The surface waves (called R waves in a semi-infinite medium) propagate cylindrically away from the source and dominate the medium response at the surface *(10)*. The propagation characteristics of these 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 from the source (50 kHz P-wave transducer) from the field testing on an asphalt pavement. The captured wave forms (full signals) include several wave components including P-waves, surface waves or R-waves and other reflected waves from the bottom surface or any other boundaries. P-waves travel faster than surface waves and thus appear before the surface wave arrival. 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-waves and R-waves are usually examined. Identifying the correct wave type is critical for accurate assessment of the wave attenuation caused by flaws present in the material.

In a homogeneous semi-infinite medium, R-wave velocity (V_R) is constant and is independent of frequency (*11*). Thus, each frequency (f) is corresponding to a certain wavelength (L_R) through the relationship:

$$V_R = f \cdot L_R \tag{2}$$

For practical purpose, however, the tested medium can be approximated as a semi-infinite medium if the wavelength of the surface waves is small when compared to the thickness of the tested medium.

3.2 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 (*12*). 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:

$$A(x) = A_o e^{-\alpha x} \tag{3}$$

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.

3.3 Wave Attenuation Parameters Selected for Assessment of Longitudinal Joints

The assessment of the joint condition was carried out as follows. The source and receiver locations at both sides of the longitudinal joint were selected to assess the relative strength of the joint in terms of wave attenuation. The spacing between the source and the receiver was selected in such a way that the captured signal has the least interference of arriving waves and the best definition of R-wave arrival among the received wave form. The wave attenuation is measured in terms of six parameters:

1. Peak to Peak (PTP) amplitude ratio in time domain;
2. Maximum magnitude ratio in frequency domain;
3. Spectrum area ratio in frequency domain;
4. Fourier transmission coefficient (FTC);
5. Wavelet transmission coefficients (WTC);
6. Equivalent damping ratio (D).

The determinations of the six parameters and the frequency distribution over time are discussed in reference (*13*). Because of page restrictions, only the results of the analysis based on WTC are presented in this paper as this is considered to be the most suitable parameter for field assessment based on the laboratory study. However, the following sections include a brief description of FTC as the process involved in the computation of the modified technique (WTC) requires good understanding of the original concept and procedures involved in the development and measurement of FTC.

3.4 Fourier Transmission Coefficient (FTC)

The Fourier transmission coefficient (FTC) method is an improved self-compensation technique developed to eliminate the variations associated with unknown characteristics of the receiver, the wave source and the coupling while assessing the condition of surface defects (*14*, *15*,*16*). This method requires two sources and two receivers placed along a line at both sides of a surface defect as shown in Figure 2. In this approach, two sources are placed at locations A and E. First, the surface waves generated at location A are recorded by a receiver at location B as a signal f_{AB} and subsequently recorded at location D as f_{AD} across the crack. The process is repeated by generating surface waves at location E and receiving f_{ED} and f_{EB} at locations D and B respectively.

The main limitation of this FTC technique is that the distance between the source and the near receiver is less than the distance between the source and the far receiver. As a result, the observed geometric attenuation of surface waves detected between the two receivers is equal to the sum of the wave attenuation associated with the presence of a surface defect between the receivers as well as the attenuation due to the difference in the source-receiver distance between the two. In addition, the geometrical effects (Lamb modes and P-wave reflections) will cause significant impact on the FTC if the spacing from the source to receivers is different (*16*).

To address this deficiency, Yang et al. (*17*) proposed an equal spacing configuration based on experimental and simulation 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 3 so that the two sides of the square run parallel to the joint (joint-free surface) while the other are perpendicular to the joint. The relative adhesive strength of the longitudinal joint based on wave attenuation parameters is determined using the following procedures

The signals detected by the receiver in Figure 3 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:

$$F_{\mathrm{S1\_R1}} = S_{\mathrm{S1}} * M_{\mathrm{S1\_R1}} * R_{\mathrm{R1}} \tag{4}$$

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.
$M_{\mathrm{S1\_R1}}$ 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:

$$F_{\mathrm{S2\_R1}} = S_{\mathrm{S2}} * M_{\mathrm{S2\_R1}} * R_{\mathrm{R1}} \tag{5}$$
$$F_{\mathrm{S1\_R2}} = S_{\mathrm{S1}} * M_{\mathrm{S1\_R2}} * R_{\mathrm{R2}} \tag{6}$$
$$F_{\mathrm{S2\_R2}} = S_{\mathrm{S2}} * M_{\mathrm{S2\_R2}} * R_{\mathrm{R2}} \tag{7}$$

Using the relationship given by the Equations 4 to 7 the amplitude ratio (FTC) between the signal across the joint and the signal through the joint-free surface is computed using the following equation.

$$FTC = \sqrt{\frac{F_{S1\_R1} \cdot F_{S2\_R2}}{F_{S1\_R2} \cdot F_{S2\_R1}}} = \sqrt{\frac{M_{S1\_R1} \cdot M_{S2\_R2}}{M_{S1\_R2} \cdot M_{S2\_R1}}} \tag{8}$$

3.6 Wavelet transformation coefficient (WTC)

The Wavelet Transform (*WT*) can be considered an additional 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 of P-waves and R waves. Many types of wavelets can be used in a wide variety of ways. A fair amount of reading and experimentation is needed to select the best option with good understanding. The goal was to choose a combination of decomposition, wavelet filter and threshold techniques which would result in the best accuracy and the best compression. This process provides the frequency domain representation of the windowed signal. The *WT* compares the similarities between the time signal and a window of variable size as it is time shifted along the signal. The *WT* is given by:

$$WT(a,b)=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{\infty}x(t)\cdot\psi^{*}\left(\frac{t-b}{a}\right)dt \tag{9}$$

where $x(t)$ is the time signal; $\psi(t)$ represents the window known as mother wavelet; parameter a is used to define the center frequency of $\psi(t)$; parameter b is used to time shift the window $\psi(t)$; the star denotes the complex conjugate; and the coefficient $\frac{1}{\sqrt{|a|}}$ ensures the same energy for all dilated versions of $\psi(t)$ used to measure the time signal.

For practical applications, the wavelet transform (Equation 9) is computed in discrete form, given by:

$$W_{k,m}=\frac{1}{\sqrt{k}}\sum_{n=0}^{N-1}x_n\cdot\psi^{*}\left(\frac{n-m}{k}\right) \tag{10}$$

where x_n represents the discrete-time signal over a time period given by $N\cdot\Delta t$, Δt is the time sampling interval, 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:

$$WTC=\sqrt{\frac{W_{S1\_R1}\cdot W_{S2\_R2}}{W_{S1\_R2}\cdot W_{S2\_R1}}} \tag{11}$$

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 time signals f_{S1_R1}, f_{S1_R2}, f_{S2_R1} and f_{S2_R2} respectively. The wavelet transform of each signal is computed by using the dominant frequency of the signal as the center frequency for the Morlet wavelet. 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.

4 LABORATORY INVESTIGATION

The laboratory investigation was carried out to examine the suitability of using different signal processing techniques and wave parameters 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 ($800\times600\times80$ mm) with different construction joint conditions were fabricated in the laboratory using a molding frame as illustrated in Figures 4 & 5. Having evaluated different compaction techniques, the traditional laboratory method of compaction using a hand-held hammer (15 lbs) with a tamping foot of $20mm \times 20mm$ dimension was used for the preparation of the slabs. During this process the numbers of blows were varied to produce variable densities near the joints to simulate good to poorly constructed joints *(18)*. A detailed description of the procedures used for the slab preparation is provided in reference *(4)*. 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 compaction technique. However, the jointed slabs were considered suitable to evaluate different NDT techniques identified for field evaluation.

The results showed that the FTC and WTC parameters were able to differentiate between the fair, week and poor construction joints built in the laboratory as illustrated in Figure 6. 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 pilot filed study was conducted to validate the findings of the laboratory investigation as described in the following section.

5. PILOT FIELD STUDY

The purpose of the pilot study is to evaluate the feasibility of measuring the two identified test parameters (FTC and WTC) for condition assessment of the asphalt pavement longitudinal joints in the field using two different procedures (Ultrasonic testing and impact hammer testing as described later) and select the most suitable procedure for field application. The pilot field study involved NDT testing at two sites. First, the CAPTT test site constructed in 2003 was selected. This test site is located within close proximity to the University of Waterloo campus situated in the Region of Waterloo, Ontario. The 700 m length and 8 m wide two-lane test track comprises four different surface course mixes of 50 mm thickness placed on a 50 mm thick standard municipal hot laid 4 (HL-4) binder mix. The NDT was carried out on the 100 mm thick asphalt pavement surface constructed with the standard hot laid surface mix (HL-3) used by municipalities in Ontario.

The construction joints of the test sections at the CPATT test site are in excellent condition. There is no apparent poor construction joints identified along the 700 m stretch of the test section. However, this site was selected for evaluating NDT techniques for two reasons. First, the test section was readily available to provide the first hands-on experience of testing pavement sections in the field. Second, this gave an opportunity to assess the sensitivity of the wave parameters to evaluate the construction joints in excellent condition as this condition was not achieved in the laboratory test.

5.1 NDT Methods Used for Field Evaluation

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 (> 30 kHz) waves electrically generated through a 50 kHz P-wave transmitter. High frequency waves are suitable for assessing the condition of pavement layers to a shallow depth of up to 50 mm targeting a narrow area of approximately 100 mm by 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 by 300 mm length. The signal processing and analysis techniques used were the same for both tests. However, the spacing between the source and the receiver used in the two test methods is different. It is important to judiciously select the spacing between the source and the receiver appropriate for each test method to ensure the receiver captures a well defined signal as described in the following section.

5.2 Selection of Source-Receiver Spacing for NDT field testing

The suitable spacing between the source and the receiver was selected using the following procedure. As a first step, wave velocities were determined by placing the receivers at selected locations from the source along a straight line at regular intervals as shown in Figure 7. To improve the coupling between the surface and the source/receivers, thin 25 mm diameter steel plates at 45 mm spacing were attached to the pavement surface using an epoxy resin, as shown in Figures 7 and 8. A spacing of 45 mm was selected between the steel plates initially based on the laboratory study. The P-wave velocity (V_P) of 2757 m/s and the R-wave velocity (V_R) of 1295 m/s were estimated from the wave measurements for the ultrasonic test using high frequency (Figure 9). It appears that the signal received at 90 mm spacing provides a well defined and clear signal representing P-wave and followed by the R-wave. Thus, a spacing of 90 mm was considered suitable for ultrasonic testing using for high frequency wave signal in this case.

Similar procedure was used for selecting space length for low frequency-impact hammer testing. The results indicated that the dominant frequencies of the signals produce impact hammer were approximately 2 kHz. Based on the V_R (1295 m/s) and the dominant frequency (2 kHz), the spacing of 270 mm was selected to satisfy the criteria given by Equation 1.

6 FIELD EVALAUTION

6.1 Testing at CPATT Test Site

The tests were carried out at two different joint locations identified as Location I and Location II as illustrated in Figure 7. Based on the source-receiver space requirements as discussed above, two sets of 90 mm square arrays were selected for high frequency wave UPV testing to assess the wave attenuation across the pavement joint as well as along the joint free pavement surface. The position of the square configuration was selected in such a way to include the pavement joint. At each corner of the square arrays, circular steel plates were attached using epoxy resin to improve coupling between the source/receiver and the pavement surface (Figures 7 and 8). The following section describes the test procedure used for location 1.

Two identical transmitters are placed at the diagonally opposite corners of a selected square array to generate high frequency waves of 50 kHz (e.g. s_2 and s_3 at location 1 in Figure 7). The surface waves generated by the two transmitters at s_2 and s_3 are received in sequence by a miniature accelerometer placed at r_3 to measure the first signal f_{s2_r3} across the joint and the second signal f_{s3_r3} along the joint-free surface. Subsequently similar procedures followed to measure signals f_{s3_r2} and f_{s2_r2} across the joint and the joint-free surface with the same accelerometer placed at r_2.

The condition of the joint was compared to the condition of the joint free surface in terms of WTC at Location I using the two pairs of signals, namely:

1. f_{s3_r2} , signal across-the-joint with f_{s3_r3} signal along the joint free surface and
2. f_{s2_r3} signal across-the-joint with f_{s2_r2}. signal along with joint-free surface

The condition index, WTC was calculated using the procedures described previously. A similar procedure was used to conduct six sets of impact hammer tests using 270 x 270 mm square configurations as shown in Figure 8 and the corresponding WTC values were calculated. The above tests were repeated to assess the joint condition at Location II.

The results of the analyses for all the tests are summarized in Table 1 and Table 2. As expected, WTC values are less than 1 indicating that the joint is slightly weaker than the joint free surface. The results from both UPV and Impact hammer tests are comparable for location 1. However, the slight difference between the ultrasonic test and the hammer test is noticeable but not considered significant for Location 2. As discussed before, the ultrasonic test targets a smaller area in comparison to the hammer test and as such some scatter in the results is expected particularly for sections with localized variations in the mix composition.

The frequency spectra of the received signals in each case were normalized (calibrated) to the frequency spectra of their corresponding source signals generated by the impact of the hammer. This approach ensures that the difference in wave attenuation across the joint and the joint-free surface is not due to the potential variation in the frequency of the signal generated by the manual strike of the impact hammer.

The only limitation of this approach is that the joint free surface is too close to the joint and as such the ratio may not likely provide the condition assessment in comparison to a joint free surface in good condition. To address this setback, a second method was developed by incorporating a joint-free surface away from the joint to determine if the assessment based on joint-free surface closer to the joint is acceptable. Method 2 analysis requires a common source (S3) location to compare the results from the two joint-free surfaces: one is parallel and close to the joint (S3-R3) and the other is perpendicular and away from the joint (S3-R4) as shown in Figure 5. Method 2 analysis is conducted using hammer tests because the square source-array configuration for hammer test will cover a larger area to include the joint-free surface away from the joint. Table 2 shows the results of the analysis indicating that the results are comparable to the results obtained using method 1 in this case. However, it was decided to use both methods for the pilot study on Hwy 401.

6.4 Evaluation of Longitudinal joints on Hwy 401 using Seismic Wave Technology

As a follow up of the test conducted on CPATT test site, additional field tests were carried out in August 2007 on Hwy 401 as shown in Figures 10 and 11 using the procedures described above. These field tests involved the evaluation of existing deteriorated joints, newly echelon paved and non-echelon paved joints. The preliminary UPV test results showed (Figure 12) that the proposed condition index or transmission coefficients, WTC for deteriorated joints are less than 10%. For non-echelon joints, the WTCs are between 60% to75 %, and for echelon paving, the WTCs are greater than 90%.

The hammer test results show the same trend but higher WTC, for poor and acceptable joints. The probable reason for the high WTC 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. This means that WTC of less than 10 % from the UPV test for poor joint means that the joint was badly deteriorated at the top 50 mm deep cracked joint in comparison to the overall depth of the joint. This makes sense because the most of the joint deterioration starts from the surface and extends towards the bottom.

7. 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 pilot field study. The field study indicates that the NDT test protocol developed based on the laboratory investigation is suitable for field application. More specifically, the findings of this study are summarized as follows:

1. The wave-based technique is suitable to assess the condition of the joint. The two sets of measurements across the joint using different methods gave average range of WTC values between 0.9-0.96 indicative of a good joint at the CPATT test site as expected.
2. Both ultrasonic and impact hammer tests are suitable for the test. The ultrasonic test will be more suitable to target smaller areas with specific problems while the impact hammer is suitable for general applications
3. The field test on Highway 401 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 traditional method and the echelon paving method.

8 FUTURE WORK

Future work will focus on numerical simulation study to assess the effect of various field conditions on WTC measurements. Typically, the joint surface is not vertical but tapers down (approximately at 30^o-45^o) from the top to the bottom of the previously paved lane (cold lane). So, the actual joint may extend from 40 mm to 90 mm depending on the thickness of HMA mat and the type of method used for longitudinal construction. In addition, the knowledge of the effect of varying thickness and the joint space on WTC is critical. Depending on the field condition, the slope may vary from location to location which may affect the measured WTC values as well. Field conditions are inherently varied; thus, the new methodology cannot be tested in the field for all possible scenarios because of cost and time limitations. However, numerical simulations represent a cost-effective alternative. Once numerical models have been calibrated and verified with the existing tests results, they can be economically used to assess the condition of the joints using the WTC technique in a variety of field conditions. Traditional field-testing can be numerically simulated using the results of the laboratory and field-testing done so far. This approach eliminates the need for extensive physical testing. In summary, it provides a virtual laboratory where by the influence of joint slope on WTC can be evaluated.

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TABLE 1 WTC values for ultrasonic tests

Test type	Location	Analyzed portion	Equation for WTC	WTC
Ultrasonic Tests (UPV)	**1**	Full signal at 54 kHz	$\sqrt{\frac{M_{s2\_r3} \cdot M_{s3\_r2}}{M_{s2\_r2} \cdot M_{s3\_r3}}}$	0.92
	2	Full signal at 54 kHz	$\sqrt{\frac{M_{s6\_r7} \cdot M_{s7\_r6}}{M_{s6\_r6} \cdot M_{s7\_r7}}}$	0.88
	Average for Locations I and II	Full signal at 54 kHz	$\frac{Location\ I\ WTC + Location\ II\ WTC}{2}$	0.90

TABLE 2 WTC values for impact hammer tests

Test type	Location	Analyzed portion	Equation for WTC	WTC
Impact Hammer Testing	**I**	Full signal at 3 kHz	$\sqrt{\frac{M_{S2\_R3} \cdot M_{S3\_R2}}{M_{S2\_R2} \cdot M_{S3\_R3}}}$	0.93
	2	Full signal at 3 kHz	$\sqrt{\frac{M_{S6\_R7} \cdot M_{S7\_R6}}{M_{S6\_R6} \cdot M_{S7\_R7}}}$	0.98
	Average for Locations I and II	Full signal at 3 kHz	$\frac{Location\ I\ WTC + Location\ II\ WTC}{2}$	0.96

TABLE 3 Condition Index (Method 2) for Impact Hammer Testing

Location	**Analyzed portion**	**Equation for magnitude ratio (*MR*)**	**Ratio**
I	Full signal at 3 kHz	$\sqrt{\frac{M_{S2\_R3}}{M_{S2\_R1}}}$	0.94
		$\sqrt{\frac{M_{S3\_R2}}{M_{S3\_R4}}}$	0.98
II	Full signal at 3 kHz	$\sqrt{\frac{M_{S6\_R7}}{M_{S6\_R5}}}$	0.97
		$\sqrt{\frac{M_{S7\_R6}}{M_{S7\_R8}}}$	0.99
Average	Full signal at 3 kHz	$\frac{Location\ I\ \ MR + Location\ II\ \ MR}{2}$	0.97

Note: *M* denotes Max magnitude of the frequency spectrum

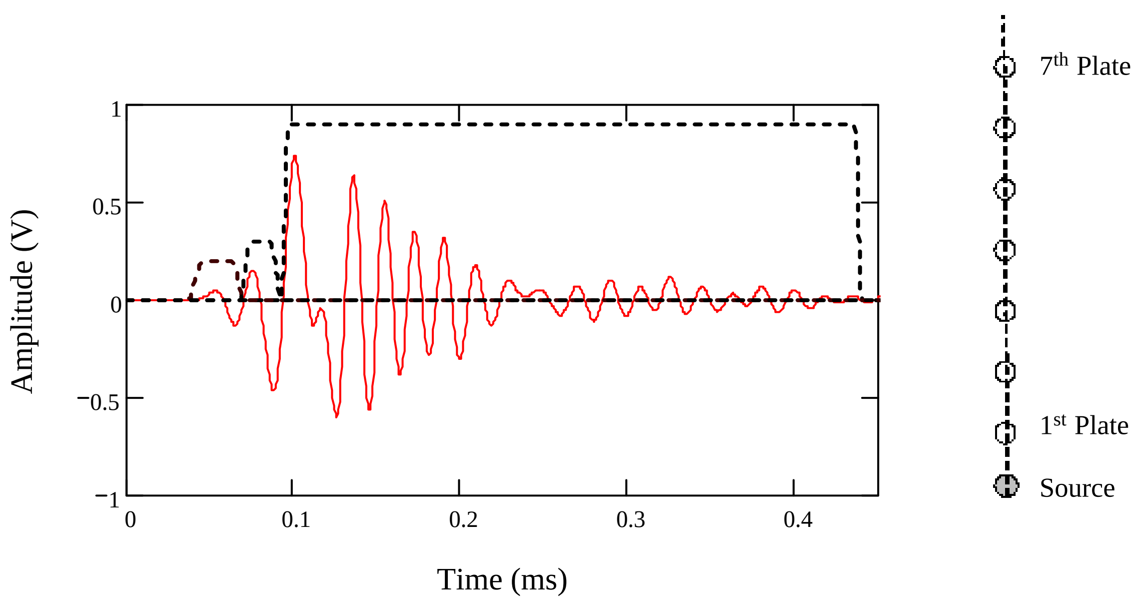


FIGURE 1 The full signal received at 90mm from the source from the field testing

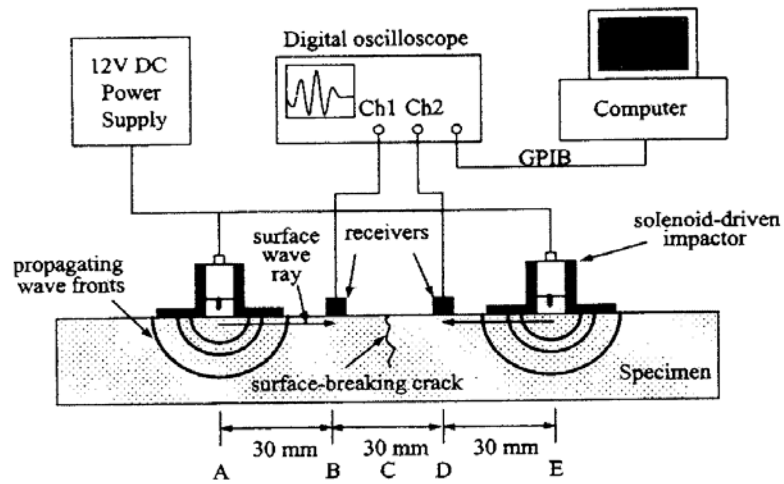


FIGURE 2 Test set up for the measurement of Transmission Coefficient (TC) (*20*)

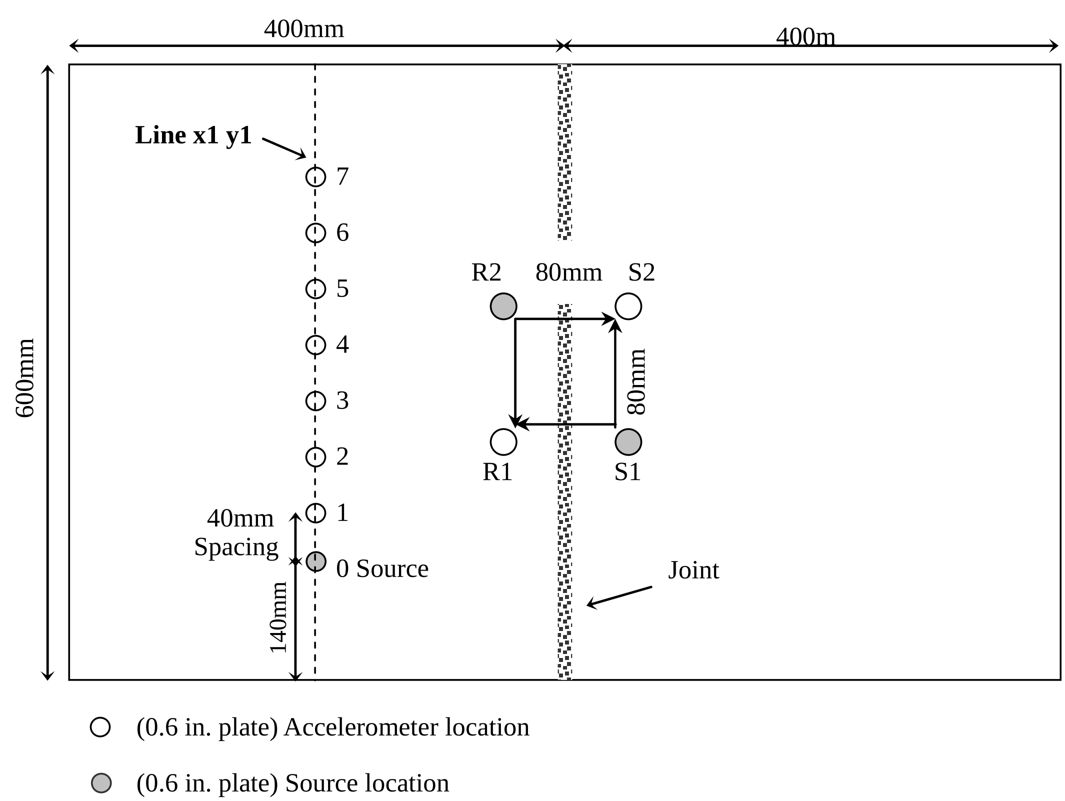


FIGURE 3 Improved ultrasonic testing geometry

Figure 4 Molding frame used for laboratory slab specimen before placing the mix

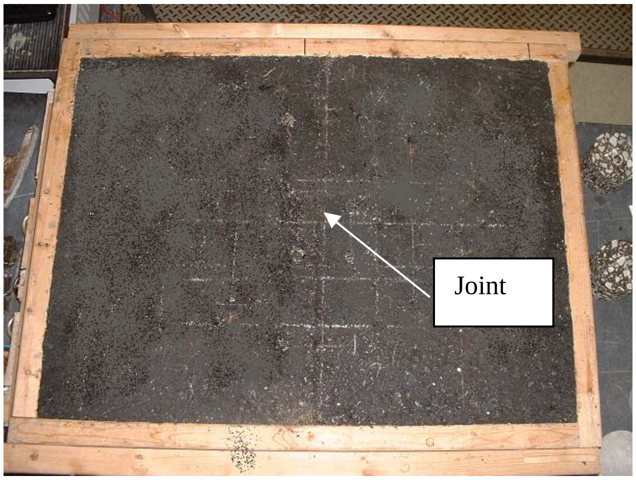


Figure 5 Laboratory slab specimen with a joint in the middle within the molding frame

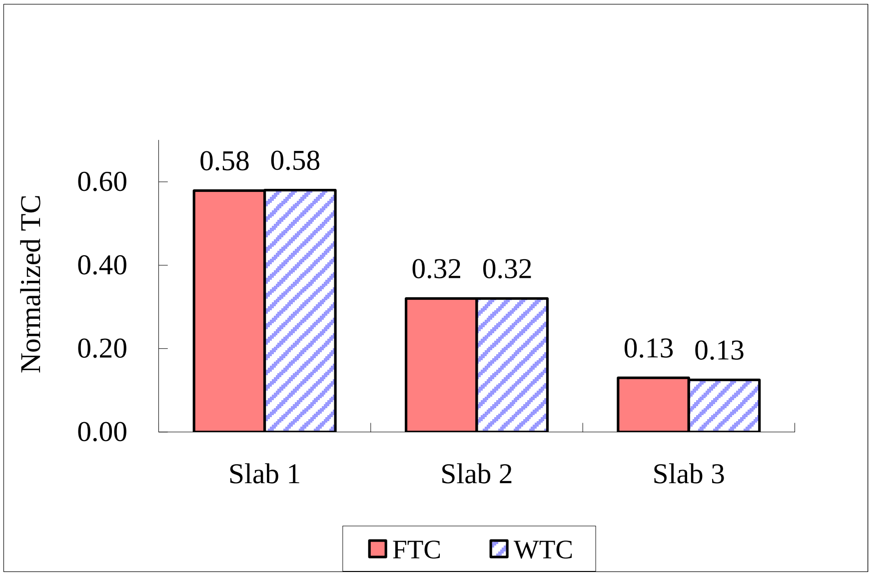


FIGURE 6 Condition assessment of joints in the slabs prepared in the laboratory (*4*)

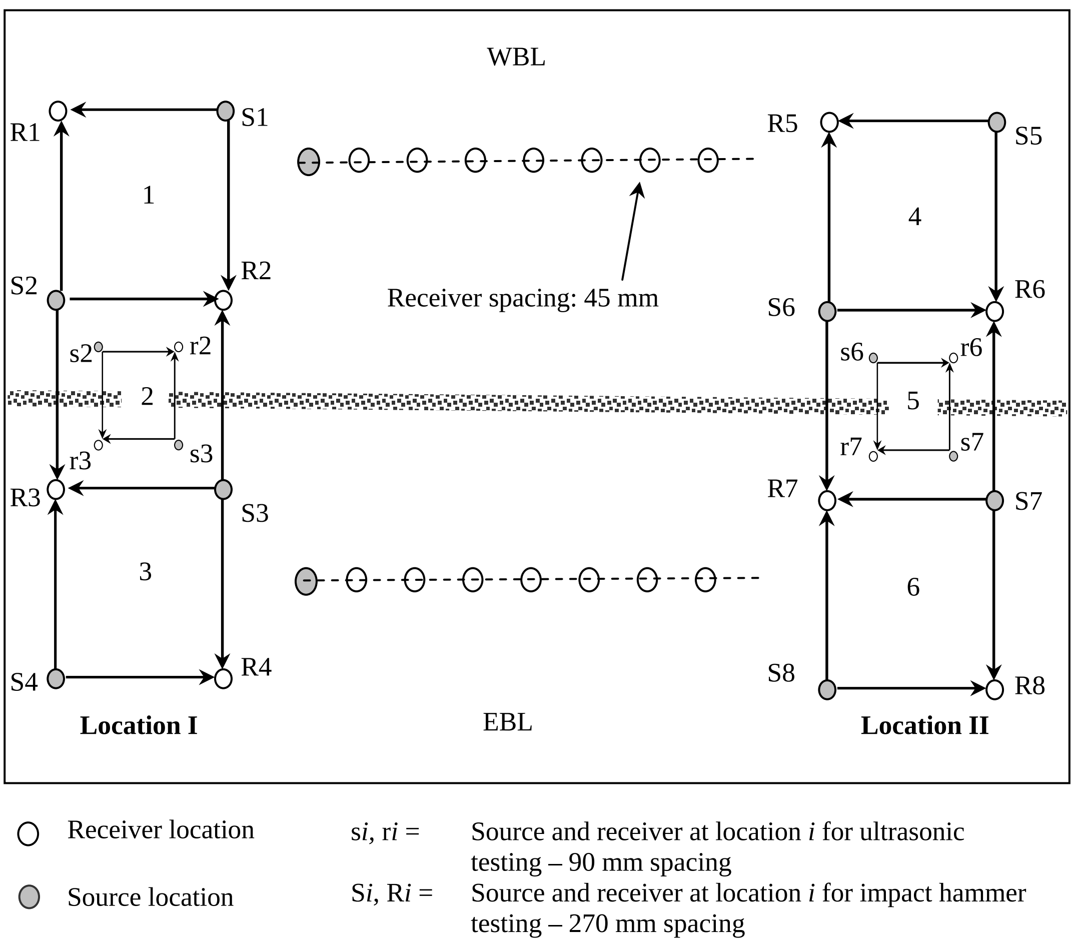
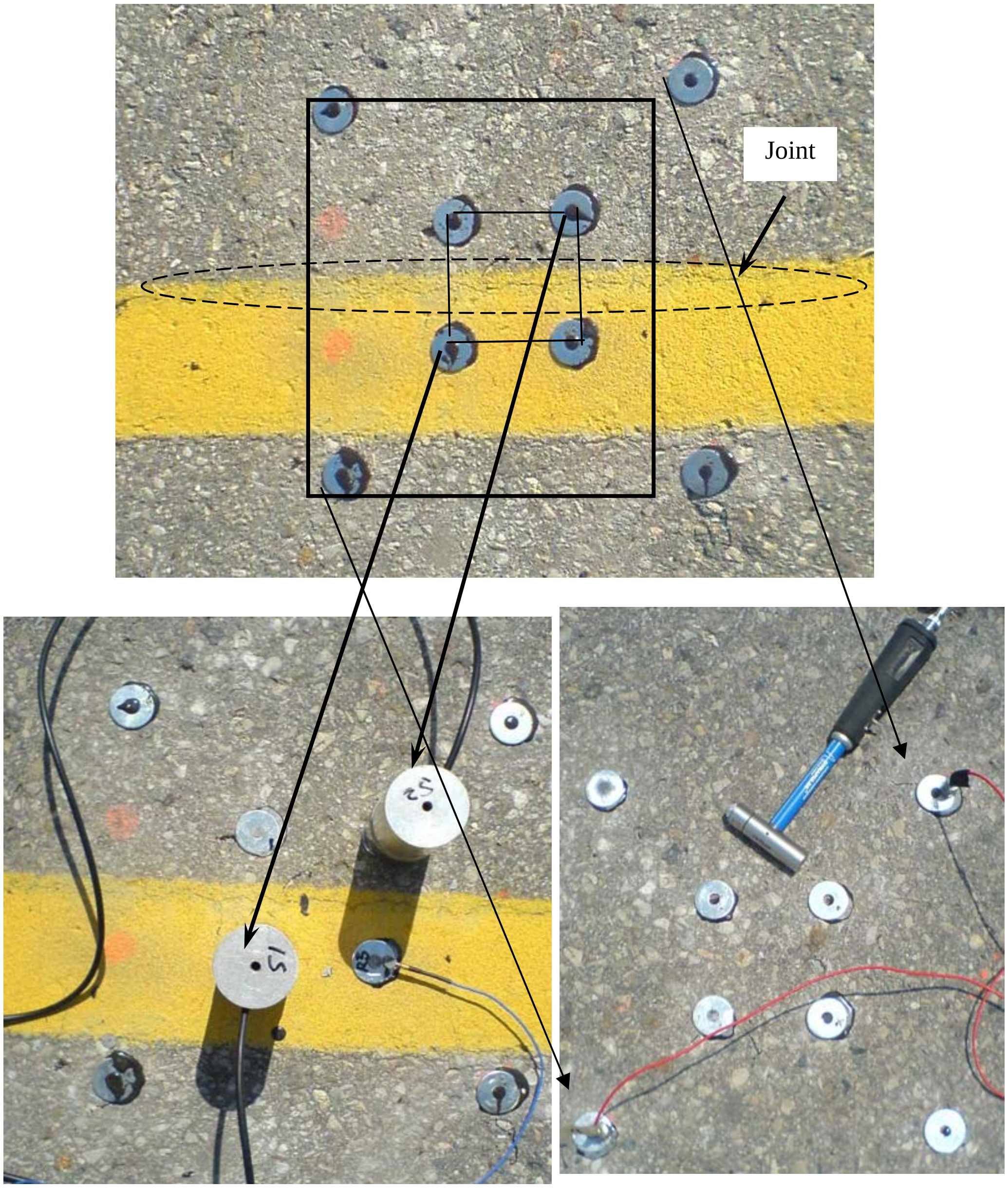


FIGURE 7 Source - receiver arrangements for testing



(a) Ultrasonic testing **(b) Impact hammer testing**

FIGURE 8 Experimental set up for field testing

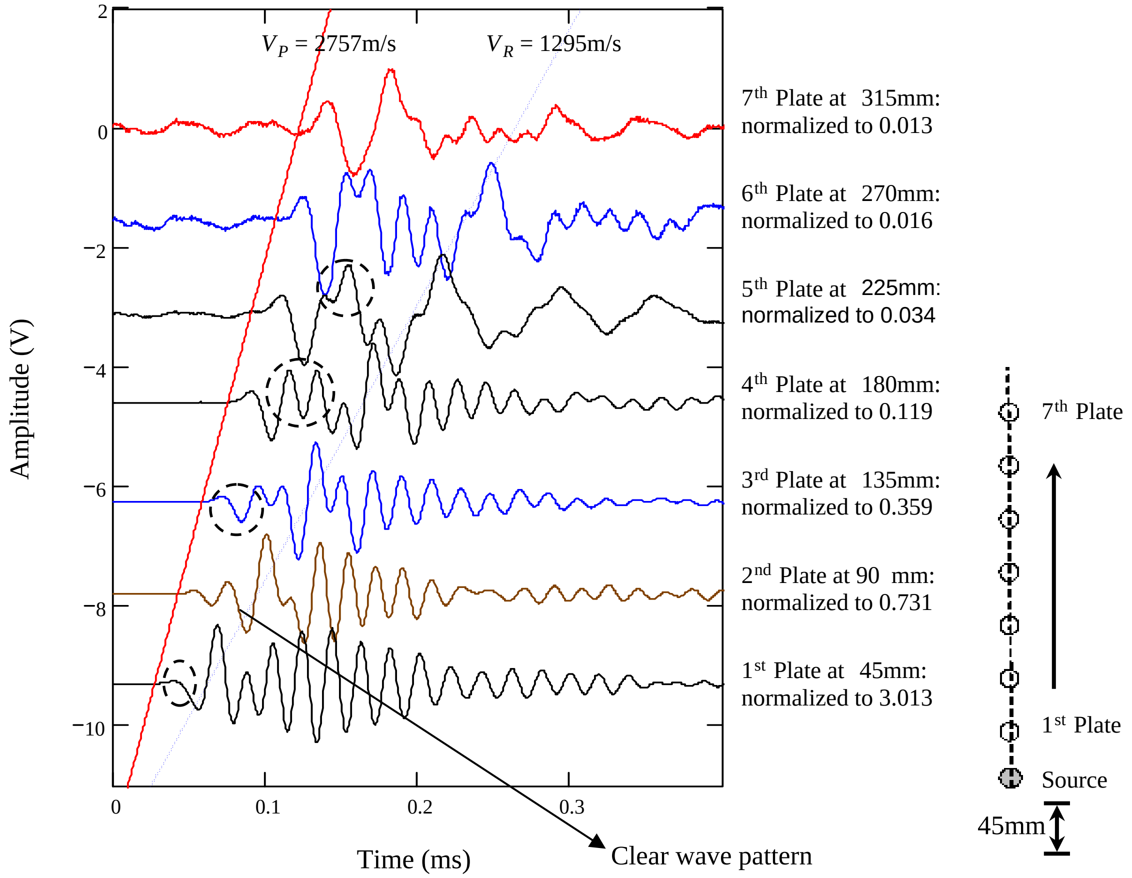


FIGURE 9 Ultrasonic wave signals received at the seven locations along the linear testing geometry - the dotted circles mark the wave interference

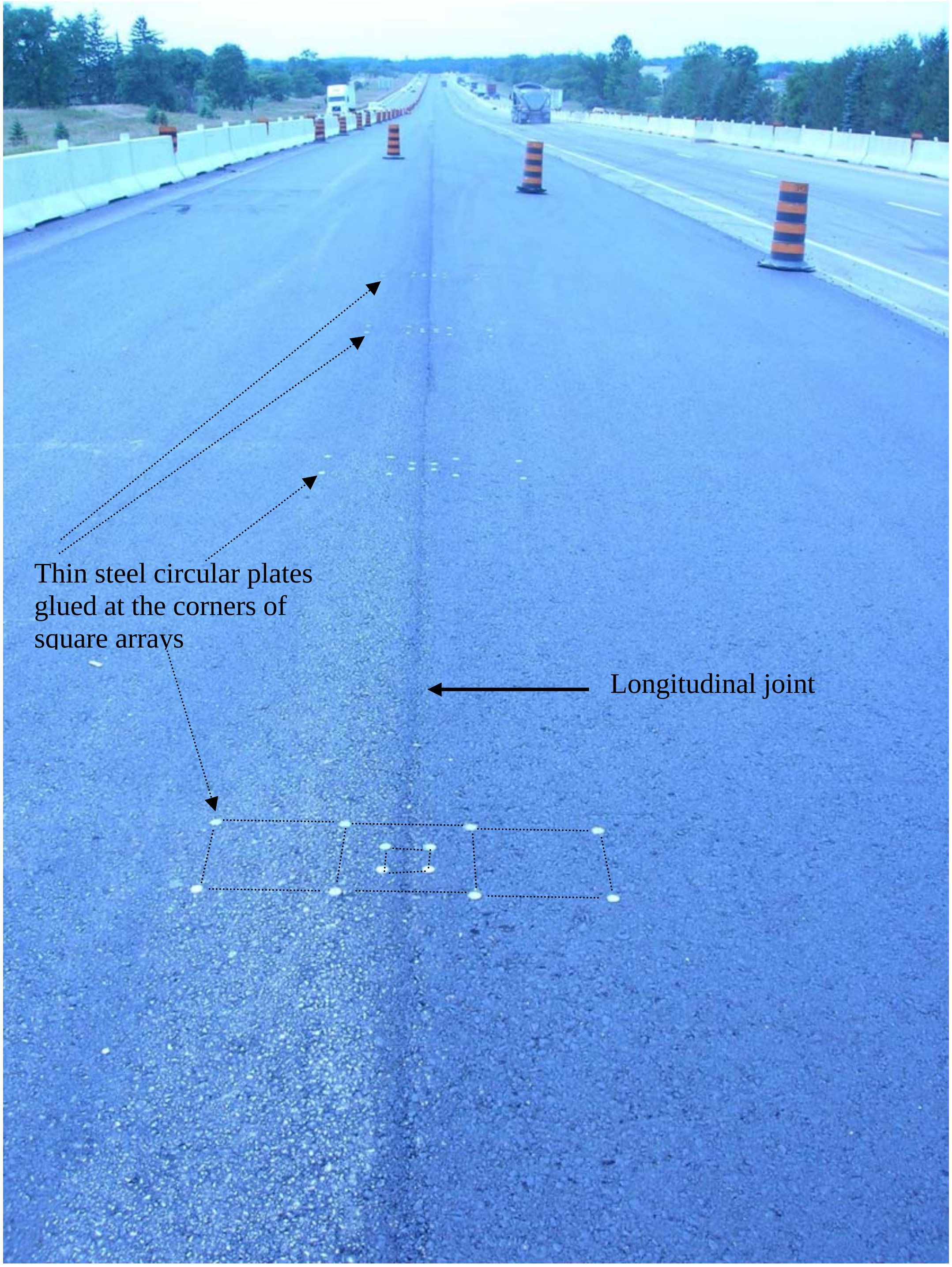


Figure 10 Thin steel plates were glued across the joint prior to testing on Hwy 401

Figure 11 NDT testing of longitudinal joints using seismic waves on Hwy 401

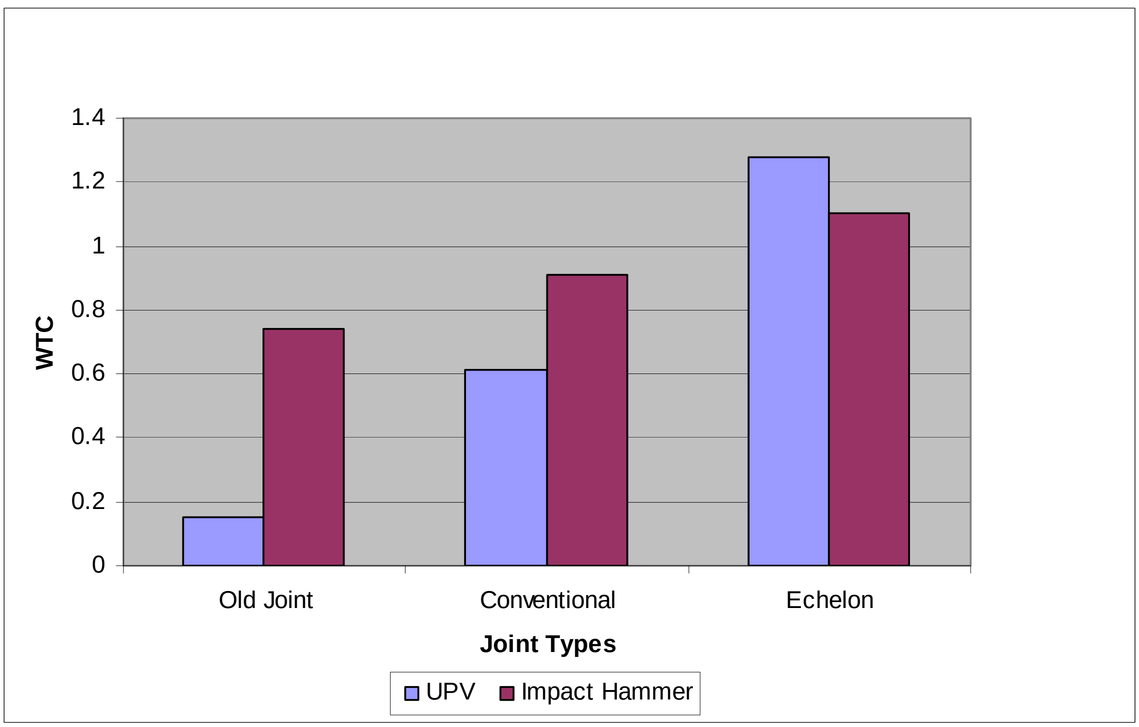


Figure 12 Seismic wave based NDT test results - Hwy 401