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By Sri Atmaja Rosyidi

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Wavelet-Spectrogram Analysis of Surface Wave Technique for In-Situ Pavement Stiffness Measurement

Sri Atmaja P. Rosyidi, Ph.D., P.Eng.

Associate Professor, Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Bantul, 55183, Yogyakarta, Indonesia, Email: atmaja_sri@umy.ac.id

Nur Izzi Md. Yusoff, Ph.D.

Senior Lecturer, Department of Civil and Structural Engineering, Universiti Kebangsaan Malaysia, 43600 Bandar Baru Bangi, Malaysia Email: izzi@ukm.edu.my

ABSTRACT

Accurate, quick, non-destructive in-situ tests for measuring pavement stiffness, or elastic modulus, is an increasingly important element in pavement management systems. This is due to the increasing number of aged road networks and the limited budget allocated by the government for pavement monitoring and maintenance. This paper aims to propose a new wavelet-spectrogram analysis of surface wave (WSSW) technique for a non-destructive testing and in situ measurement of pavement surface layers. The proposed technique was developed based on the spectral-analysis of surface wave (SASW) and modified data analysis of the ultrasonic-surface-wave (USW) methods. This technique utilizes two receivers to detect and record the signals of the surface wave propagating on a pavement surface. In wavelet analysis, the received signals are transformed into a time-frequency domain and displayed in a spectrogram. The spectrogram was generated based on the mother wavelet of Gaussian derivative (GoD). A wavelet filtration technique was also used in the time-frequency spectrogram to diminish the effect of the noise signal recorded during field measurement. The unwrapped phase of a different spectrum was generated from a selected wave-energy in the spectrogram to obtain a phase velocity; this is done through a linear regression analysis for calculating the value of the slope of a phase velocity. The elastic modulus of pavement surface layer can be obtained via a linear relationship of assumed density, measured phase velocity, and assumed Poisson ratio of pavement materials. The results can be used to show that the proposed technique can be of practical use for in situ elastic modulus measurement on flexible and rigid pavements. It can also be used to determine any changes that might occur in the stiffness pavement surface layer.

Keywords: elastic modulus, pavement surface layer; surface wave techniques, wavelet analysis

INTRODUCTION

SASW is one of of the frequently used non-destructive testing (NDT) methods for assessing the material strength of pavement structures. This method uses the dispersive characteristics of seismic surface wave to determine the stiffness profile of shear wave velocity which corresponds with the elastic modulus of a pavement layer. This method comprises three steps of data analysis, i.e., (1) recoding the signals and analyzing its spectrum based on the measured seismic waves propagation, (2) generating experimental dispersion curves from the results of phase velocity analysis, and (3) inverting the experimental dispersion curves to generate a shear wave velocity profile. Researchers have conducted studies on the various ways the SASW method was used. Amongst them are the use of SASW for soil characterization (Stokoe et. al. 1994, Kim et. al. 2001); evaluation of dynamic soil properties (Rosyidi and Taha 2012); pavement investigation (Rosyidi et. al. 2007, Yusoff et. al. 2013, Rosyidi, 2017); and measuring of the stiffness of asphaltic pavements (Shirazi et al. 2009, Hazra and Kumar 2014).

In order to generate a stiffness profile, or shear wave velocity, of a pavement, an advanced mathematical approach was used to invert the SASW method. Several elastic stress wave theories for solids have been developed to derive theoretical dispersion curves in the attempt to produce a reliable inversion analysis. Among them are the transfer and dynamic stiffness matrix, which use plane-wave approximations and assume that the pavement system comprises profile layers with homogeneous and isotropic properties; generalized reflection-transmission coefficient; finite element; and finite difference methods. These inversion processes utilized existing information of model parameters in an initial profile consisting of a set of horizontal homogeneous layers with constant stiffness in the horizontal direction overlaying a half-space. Layer thickness, stress wave velocities (shear and compression wave), Poisson's ratio of the material and density are assigned to each layer of the profile. A change in the Poisson's ratio and density of the material has a negligibly small effect on the calculated dispersion curve (Tokimatsu et al., 1992). This initial profile is then used as a basis for calculating a theoretical dispersion curve by using one of the elastic stress wave theories. Once a theoretical dispersion curve has been obtained, the inversion method is iteratively implemented by comparing the theoretical curve with the experimental data. This comparison is done by calculating the error between the theoretical and experimental data, such as the root mean square error. If the match is not acceptable or if the error of the dispersion curves is large, the initial profile is updated and the new profile is used to produce a new theoretical dispersion curve. The process is iterated until both curves match, and only matched theoretical curve are considered as a real profile. However, in the case of an irregular profile such as pavements, the inversion process becomes more difficult and requires extended data processing time. Many researchers have elaborated on the difficulties they encountered when applying the SASW method on pavement profile. Al-Hunaidi (1992), Tokimatsu et. al. (1992), Ganji et. al. (1998), Ryden et. al. (2004) reported that most of the difficulties are due to the effect of higher modes stress wave propagation.

The conventional stress wave propagation analysis in the SASW inversion method is not capable of directly distinguishing between the fundamental and the higher modes that occurr in a pavement system. It is also unable to clearly observe the stress waves propagation superposition modes if it is only based on the field configuration and receiver locations. This effect, which is also known as apparent phase velocity, varies with distance and has an effect on receivers position for data analysis and the fundamental and higher- modes superposition for the inversion analysis. Ryden et. al. (2004) proposed a new approach for conducting seismic testing on pavements. This method is able to distinguish stress wave propagation modes, thereby solving some of the difficulties commonly encountered in pavement testing. They used a multichannel simulation with one receiver (MSOR) method, which was developed from the concept of multichannel analysis of surface wave (MASW) which typically requires a minimum of 48 receivers, to gather data. Results show that the dispersion of stress waves in a pavement profile for a frequency of between 50 to 3,000 Hz cannot be represented with only one average dispersion curve. The high frequency range of the dispersion curve is matched with theoretical Lamb waves in a free plate, while the lower frequencies are matched with several branches of dispersion curves which correspond with each layer of the varying stiffness in the pavement profile. However, due to the complexity in interpreting surface wave as well as the tedious and complicated data analysis, the MASW and MSOR methods are not widely used in structural pavement assessment.

There is an urgent need to develop a quick, practical, accurate, cost-efficient, non-intrusive test for evaluating pavement systems since pavement maintenance and management is a cumulatively complex process due to the increasing number of aging roads and the limited budget allocated by the government. Additionally, for practical and functional purposes, pavement engineers need to be able to do rapid assessment and reasonably simple analysis to measure the stiffness of pavement surface layer.

This paper introduces a new technique for measuring surface wave which uses a combination of continuous wavelet transform and a simple formulation of phase data, phase velocity, and elastic stiffness relationships to determine the surface stiffness of a pavement structure. This technique is known as the wavelet-spectrogram analysis of surface wave (WSSW). A continuous wavelet transforms

(CWT) is used to decompose the received seismic signals and to identify and enhance the phase information from the time-frequency spectrogram. The technique is utilized to improve the phase data obtained from the signals. Seismic data in the conventional SASW method is usually processed and analyzed in frequency domain by using the fast Fourier transforms (FFT). However, since Fourier transform works by utilizing any arbitrary periodic sinusoidal function of time, the analysis is not appropriate for interpreting the spectral characteristics for non-stationary signals (Rosyidi et.al. 2009). Wavelet is being used more frequently as an effective analysis for seismic signals in the time dimension and for localizing various their spectral events. A time-frequency spectrogram can be generated in wavelet analysis to examine the signals in the time and frequency domains simultaneously. Therefore, the translation and scaling process in wavelet analysis is of particular use for measuring the influence of the varying seismic wave modes and identifying some of the modes in the time domain. Wavelet analysis also allows for a more stable computation of phase velocity in comparison to the phase velocity obtained by using the time-difference method which is commonly employed in traditional SASW. Gucunski and Shokouhi (2005) asserted that CWT analysis can be used to identify the cavities in media sub-surface, i.e. the pavement. It is also capable of differentiating between the characteristics of layer dipping and interface layers when there is an extreme change in stiffness.

This paper describes the simple procedure of using phase data from wavelet analysis and material properties to obtain the elastic modulus of pavement surface layer without utilizing any complex inversion algorithms. It then presents the typical results from some case studies which were conducted to evaluate the asphalt concrete (AC) layer of pavement structurez at two different locations, i.e., Purwakarta national highway network, Indonesia and road pavement in Bandar Baru Bangi, Malaysia. Several comparative tests of the WSSW measurement were also conducted on rigid pavements in Yogyakarta, Indonesia.

CONTINUOUS WAVELET TRANSFORM

Continuous wavelet transform (CWT) is an interactive signal processing tool used to analyze the time and frequency characteristics of nonstationary seismic signals. It has been variously employed to analyze data in soil and geotechnical investigations (Rosyidi et. al. 2009) and in geophysical methods (Foufoula-Georgiou and Kumar 1995). CWT compares signals with another version of wavelet function. Wavelets compress or stretch in such a way that the time component changes with frequency. The wavelet functions are manipulated in a translation process where the function moves along the time domain and in a dilation process where the wavelet spreads out. When the time domain increases or decreases, the frequency component of the wavelet changed into high or low frequency, respectively. Consequently, as the frequency resolution increases, the time resolution decreases, and vice versa. The ability of CWT to construct a time-frequency resolution generated by wavelet analysis is very suitable for non-stationary seismic analysis.

A wavelet is expressed as a function of $\psi(t) \in L^2(\Re)$ and, by dilating and translating the wavelet $\psi(t)$, it is possible to mathematically define a wavelet function as:

$$\psi_{\sigma,\tau}(\tau)=\frac{1}{\sqrt{\sigma}}\psi\left(\frac{t-\tau}{\sigma}\right) \qquad (1)$$

where σ is dilation parameter (it is also referred to as a scale) and τ is translation parameter (σ, τ ∈ ℜ and σ ≠ 0). The wavelet has varying basic wavelet shapes which are utilized in seismic data analysis. These shapes are known as mother wavelet, i.e., Gaussian, Daubechies Haar, Meyer, Morlet, Symlets, Paul, Biorthogonal and Mexican Hat, which dilate and translate the versions of the derived mother wavelet which are then used in wavelet analysis. The selection of a suitable mother wavelet in a particular analysis is based on the waveforms of seismic signals.

CWT can be written and derived from the family wavelets $\Psi_{\sigma,\tau}(t)$ with a signal $f(t)$ and is expressed by the following equation:

$$F_W(\sigma,\tau)=\langle f(t),\psi_{\sigma,\tau}(t)\rangle=\int_{-\infty}^{\infty}f(t)\frac{1}{\sqrt{\sigma}}\overline{\psi}\left(\frac{t-\tau}{\sigma}\right)dt \qquad (2)$$

where $\overline{\psi}$ is the complex conjugate of ψ, and $F_W(\sigma,\tau)$ is the time-scale plot.

In this study, the Gaussian Derivative (GoD) was used as the mother wavelet. The real GoD wavelet component in the time (t) and frequency ($s\omega$) domains can be expressed as:

$$\psi_0(t)=\frac{(-1)^{m+1}}{\sqrt{\Gamma\left(m+\frac{1}{2}\right)}}\frac{d^m}{d\eta^m}\left(e^{-t^2/2}\right) \qquad (3)$$

$$\hat{\psi}_0(s\omega)=-\frac{i^m}{\sqrt{\Gamma\left(m+\frac{1}{2}\right)}}(s\omega)^m\left(e^{-(s\omega)^2/2}\right) \qquad (4)$$

where m and Γ are wave number and Gamma function, respectively. Hence, the complex wavelet form of GoD in the frequency domain can be created by using a Heaviside function where the wavelet decays with the square root of a gamma function. In the GoD mother wavelet, the shape of the wave is essentially determined by the wavelet derivative order. Thus, the best resolution of the waveform can be simply obtained by varying the derivative order.

RESEARCH METHOD

Field Measurement

In the WSSW method field measurement of seismic data is done by dropping steel ball bearings weighing between 5 and 15 g to generate seismic waves on the pavement. Two high-frequency accelerometers (25 kHz) are employed to detect the signals of seismic waves. Both accelerometer receivers are located in a linear array with the source. The signals are then recorded in a set of ADT analog-digital acquisition which is connected to a computer unit used to analyze the spectrum of signals (Figure 1). The configuration of mid-point receiver spacings employed in this study is shown in Figure 2. The field mid-point receiver spacing and receiver-source spacings were arranged for sampling different depths and layers of the pavement structures. The receiver spacing (as shown in Figure 2 as d_2) is less than and/or equal to the thickness of the layer (H). The distance from the source to the first receiver (d_1) must be equal with the receiver spacing (d_2). Since measurement was made on the surface layer of flexible and rigid pavement structures, short receiver spacings of 5, 10, 15 to 30 cm were utilized. In order to enhance signal quality and minimize the shifting of internal phase between receivers, the forward and backward procedure of the test configuration was repeated at least 4 to 6 times for each spacing measurement. This repetition was also used to verify the variability and consistency of the results of the WSSW test. This paper also discusses the result of the statistical analysis of the various repetition procedures.

In addition to the WSSW test, comparative tests, i.e., spectral analysis of surface wave (SASW). falling weight deflectometer (FWD), and laboratory resilient modulus tests, were also conducted at three different sites, i.e. existing flexible pavement of a national road network in Purwakarta, West Java, Indonesia; a campus road in Universiti Kebangsaan Malaysia (UKM), Malaysia; and a new rigid pavement in Yogyakarta, Indonesia. SASW and FWD measurements were made at the same locations of the road pavements. Pit test was also conducted to determine the number of layer and the materials of the pavement profile. The result of the pit test show that the measured pavement comprises three layers, i.e., 18 cm of asphalt concrete (AC), 10 cm of crushed stone base, and 30 cm of sub-base overlaying the compacted subgrade materials. Another comparative test, i.e., resilient modulus laboratory test, was conducted on existing flexible pavement at the Universiti Kebangsaan Malaysia (UKM) Campus, Malaysia. The pavement profile at UKM campus sites consists of an AC layer (7 cm) and a base layer of crushed aggregate (40 cm) over a soil subgrade layer. The WSSW measurement of rigid pavement was validated by conducting a compressive test on new PCC slabs 45 cm thick over a compacted layer of sand.

Proposed Data Analysis in the WSSW Method

The following scheme for the WSSW method is proposed based on the seismic data analysis using continuous wavelet transform and calculation of the elastic modulus of pavement:

1. Measure the field seismic surface wave by using the mid-point receiver spacing configuration (Figure 2).
2. Compute the time-frequency spectrogram of CWT based on the Gaussian Derivative (DoG) mother wavelet for the received signal waveforms. The generated spectrogram will provide information of the varying wave modes effects, energy events of the spectrum, and the manner in which higher modes diverge in time.
3. Analyze the phase difference in the transfer function spectrum from the TF spectrograms of the signal recorded by the first and second receivers. The mathematical equation for the computation of phase spectrum is based on the wavelet spectrogram and is expressed as (Rosyidi & Taha, 2012, Rosyidi, 2017):

$$H(f)=\frac{Y(f)}{X(f)}\approx\frac{W_{f\ (u,s)}^{Y}}{W_{f\ (u,s)}^{X}}=\frac{\int_{-\infty}^{\infty}Y(t)\frac{1}{\sqrt{\sigma}}\psi^{*}\left(\frac{t-\tau}{\sigma}\right)dt}{\int_{-\infty}^{\infty}X(t)\frac{1}{\sqrt{\sigma}}\psi^{*}\left(\frac{t-\tau}{\sigma}\right)dt} \quad (5)$$

where,

X(f) = signal input in the frequency domain from first receiver *X(t)*,

Y(f) = signal output in the frequency domain from second receiver *Y(t)*,

$$W_{f\ (u,s)}^{Y}=\int_{-\infty}^{\infty}Y(t)\frac{1}{\sqrt{s}}g\left(\frac{t-u}{s}\right)e^{-i\xi(t-u)} \quad (6)$$

$$W_{f\ (u,s)}^{X}=\int_{-\infty}^{\infty}X(t)\frac{1}{\sqrt{s}}g\left(\frac{t-u}{s}\right)e^{-i\xi(t-u)} \quad (7)$$

A phase spectrogram in the time-frequency domain based on Eq.6 and Eq.7

can be computed using the following equation:

$$H(u,s) = \frac{W_f^{XY}(u,s)}{W_f^{XX}(u,s)} = \frac{\left|W_f^{XY}(u,s)\right| e^{i(\theta_Y(a,b) - \theta_X(a,b))}}{W_f^{X}(u,s)^* \times W_f^{X}(u,s)} \quad (8)$$

Thus, phase difference is calculated as a ratio of the imaginary to the real part of the phase spectrogram, which is expressed as:

$$\phi = \tan^{-1}\left(\frac{\Im H(u,s)}{\Re H(u,s)}\right) \quad (9)$$

4. Determine the coherence function spectrum to evaluate the quality of signals recorded by both receivers. The coherence value is scaled in real number from zero to one within the range of the measured frequencies. A value of one indicates a good signal and the best correlation between the two observed signals while a value of zero indicates a bad signal and lack of correlation between the two signals. The coherence function was obtained by using the following formula (Rosyidi, 2017):

$$\gamma^2(f) = \frac{W_f^{yx}(u,s) \cdot W_f^{yx}(u,s)^*}{W_f^{xx}(u,s) \cdot W_f^{yy}(u,s)} \quad (10)$$

5. Generate a trendline of linear regression relationship from phase difference versus frequency. Phase velocity is then calculated as a function of the slope value (m) of linear regression line. The mathematical formulation for the phase velocity and the slope is expressed as:

$$\phi = \left|\frac{360D}{V_{ph}}\right| f = mf \quad (11)$$

The phase velocity given by Equation 11 is determined from the slope of the obtained best-fit line (m). In this formulation, the phase velocity is assumed to be independent of the wavelength with a value approximately equal to the thickness of the uppermost layer. The range of the wavelength can be assessed from the relationship of phase velocity and its frequency (f):

$$\lambda = \frac{V_{ph}}{f} \quad (12)$$

6. Calculate the dynamic elastic modulus (E) of the pavement materials by using Formulas 13 and 14 (Baker et al, 1995):

$$E = \frac{\gamma}{g}\left|KV_{ph}\right|^2 \quad (13)$$

$$K = (1.13 - 0.16\mu)\sqrt{\frac{2(1-\mu)}{(1-2\mu)}} \quad (14)$$

where V_{ph} is phase velocity, g is acceleration of gravity, γ is total unit weight of the material, and μ is the assumed Poisson's ratio. It should be noted that, in the WSSW technique, the materials on surface layer of the pavement are assumed to be uniform when the

high-frequency surface waves were generated.

RESULTS AND DISCUSSION

Application of WSSW on Flexible Pavement

In situ Measurement of the Elastic Modulus of Surface Layer

WSSW tests were carried out at twelve locations of road-flexible pavements on the national highway network in Purwakarta, Indonesia. Figure 3 shows the example of the signals from the WSSW measurement. The groups of body and surface waves from the recorded signals can be explored, as shown in Figure 3These signals were used to generate a time-frequency (TF) spectrogram plot by using the CWT of GoD. The spectrogram of CWT can be used to solve the problems of identifying spectral events of the seismic signals obtained from field measurement. The spectrogram shows the energy of measured signals as a linear combination in signal which is shifted by Gaussian Derivation functions in time and frequency domain. This technique is effectively used for a good tool in investigation of wave group in energy events. A typical CWT spectrogram in the time-frequency resolution plot of the signals is shown in Figure 4. It shows two distinct energy from the wave propagation events in the wavelet spectrogram. The energy amplitude distribution in both spectrograms are displayed in a normalized-dB unit. The wave group which arrived early has been identified as a lower mode of seismic waves. The frequency band of the lower energy ranges from 2.8 to 16 kHz. Within this spectrum range, the wave mode has been identified as coming from the surface wave signals. The energy level of the lower mode of seismic signals can detect up to 60 % of total wave energy through independent measurement of surface wave propagation. The wave group which arrived later was identified from direct and reflected body waves. The waves which arrived later have higher frequency and is the higher mode of seismic waves. This mode occurs at frequencies greater than 16 kHz. The result of the CWT spectrogram indicates that the dominant wave energy of the surface waves at the frequency range of interest can be clearly observed. The spectrogram provides information on wave mode with a clear time-frequency resolution at high frequency signals. It can be used to interpret the group frequency bandwidth by using various derivation order of the Gaussian mother wavelet.

Figure 4 shows the calculated phase difference of seismic signals in the frequency domain which were determined from both wavelet spectrograms. Without information on the observed energy wave groups, the wrapped phase could produce erroneous phase velocity. The separation of energy wave group of interest can be done by extracting the selected dominant energy event of surface wave group from the CWT spectrogram. In this study, the energy event of surface wave detected between 2.8 to 16 kHz was extracted and the wrapped phase difference was then measured from the transfer function spectrum, as shown in Figure 5. The wrapped phase data is represented with a value of between -π and π radian (or -180 and 180 degrees) which makes it easier to observe the detailed variation in the phase data in a small space of graph. By using the wavelet spectrogram approach to extract the selected energy wave group of surface waves, the phase difference from transfer function spectrum shows clear saw-tooth patterns since the phase spectrum for the most part carries the dominant energy event of a wave group at a given frequency. It also shows that the time-frequency CWT spectrogram of the Gaussian Derivative wavelet can be effectively used to generate enhanced phase spectrum with a better, smooth, clear pattern than the traditional phase unwrapping by Fourier analysis that is usually done in the SASW. Figure 6 compares the phase spectrum obtained by using CWT and Fourier analysis. The transient wave pattern from seismic waves is usually sparse in the wavelet (Ching et al., 2004). Their investigation shows that, compared to the Fourier domain, the wavelet domain is a better platform for estimating the function for transient wave pattern since the pattern can be easily differentiated from the signals, higher mode reflected signals, and noise. Another related work by Gucunski and Shokouhi (2005) proved the advantage of using wavelet transform in spectral analysis since it is capable of giving a more stable computation of phase velocity and can be used to characterize layer interface. In this study, WSSW can be used to characterize and extract the energy event of wave groups from the surface wave and reflected body waves.

Figure 6 shows a comparison of the wrapped phase spectrum generated through Fourier analysis and wavelet analysis. It is interesting to note that the wavelet analysis extracted from phase spectrum of interest produced a better and smoother pattern compared to the Fourier domain, as discussed above.

Figure 5 shows that the phase difference spectrum has a clear saw-tooth pattern in the frequency domain of up to 25 kHz. With regards to the phase data, the high-frequency mode of surface waves is represented as a pavement surface layer with a high stiffness (elastic modulus). In this case, the coherence function was used to inspect the quality of phase difference spectrum. Figure 6 shows that the phase data with a frequency of up to 20 kHz has a coherence magnitude greater than 0.98.

For a given phase difference spectrum, the elastic modulus of a pavement surface layer can be calculated by fitting a smooth curve of the weighing function. The smoothed phase spectrum was generated and fitted to the raw data points of phase difference. The phase spectrum was then unwrapped by counting the number of cycles from the peak sequence of the wrapped phase spectrum, as shown in Figure 7. The linear regression analysis was then generated on the phase spectrum as the best fit trendline of the phase difference. The slope of the line is almost similar with the measured frequency. The value of the slope was then substituted into Equations 11, 13 and 14 to determine the elastic modulus of the surface layer material. As can be seen in Figure 7, the trendline for the frequency range coincides with the wavelengths that are less than the thickness of the surface layer.

Figure 7 shows that the slope (*m*) of the trendline has a value of 0.0140 and is the best-fit curve. Using Equation 13 to compute the phase velocity gives a value of 1,028.57 m/s. By using the calculated phase velocity, a field configuration with a receiver spacing (d_2) of 5 cm; assumed Poisson's ratio of 0.25 for pavement material such as asphaltic (Asphalt Concrete/AC) layer; and a unit weight of 2,200 kg/m^3, the elastic modulus was then computed to be 845,662,040.80 kg/m^2 (8,456.62 MPa). This value was obtained when measurement was made at a pavement surface temperature of 31.8°C. The measured modulus is the typical value of an AC modulus when measured at a small strain level, which is similar to the findings made by Nazarian and Stokoe (1986), Stokoe et al. (1991), Roesset et al. (1991), Aouad et al. (1993), Aouad et al. (2000), and Yuan et al. (2015). Aouad et al. (1993) have proven that the seismic method is effective for determining in situ changes in stiffness (E) at temperatures ranging from 30°F to 143°F.

In general, this result indicates that the elastic modulus of the pavement surface layer can be simply determined by using the WSSW technique. However, the elastic modulus obtained in this study are relatively high. This is because the seismic technique evaluates the modulus at a very low strain level (less than 10^3 %). The behavior of material modulus at this strain level could be considered as the maximum moduli due to its very small strain amplitude. This finding is supported by a previous observation made by Roesset et al. (1990). In addition, if the elastic modulus of asphalt concrete is a function of frequency, the modulus obtained from seismic measurement will give higher stiffness values than other dynamic and static tests due to the high frequency used in the seismic tests. Consequently, adjustment should be made to the seismically determined stiffness

(Stokoe et al. 1991) by constructing a master curve for temperature correction and frequency shift (Kweon and Kim, 2006; Ryden, 2011; Gudmarsson et al. 2012). In the attempt to illustrate the sensitivity and utility of WSSW method for measuring changes in stiffness, in situ WSSW tests were performed on constructed road-pavement and pavement overlay. Figure 8 shows that the different layers of stiffness of both pavement profile have been investigated satisfactorily. The road-pavement surface and overlay layer were evaluated using a 10- and 5-cm receiver spacing configuration, respectively. The properties of both surface layers were determined definitively without any complex inversion process that is usually required in the SASW method. The change in the stiffness of the surface layer can also be evaluated non-destructively and quickly by using the WSSW technique. The WSSW method, however, can only be used in two obvious conditions: first, it is only effective when the wavelength is less than and/or equal to the uppermost thickness of surface layer. When the wavelength is greater than thickness of the layer, the dispersive surface wave velocity is significant influenced. Secondly, the material properties of the pavement surface layer are assumed to be uniform and modulus is measured at very low strain levels and high levels of frequency. The elastic theory is used to explain the response of material associated with this measurement where the response of material is predominantly linear (Luna & Jadi, 2000).

Validation by using the SASW and FWD Test

As shown in Figure 8, the result was then validated by conducting spectral-analysis-of-surface-wave (SASW) tests at the same locations where the WSSW tests were performed. In the SASW method, impact sources, i.e. ball bearings and hammers, were used to produce the energy of surface wave propagating horizontally in the sub-surface layer of the pavement. Various receiver and source configurations were used with mid-point receiver spacings of 5, 10, 20, 40, 80 and 160 cm to examine the pavement profile. Short receiver spacings of 5 and 10 cm were used with ball bearings as a source of high frequency to sample the pavement surface layers; longer receiver spacings of 20 to 160 cm were used along with small- to medium-sized sledge hammers as low frequencies sources to observe the response of base and subgrade layers. DJB A/123/E piezoelectric accelerometer and Harmonie 01 dB (IEC 651-804 Type-I) ADC (analog digital converter) were connected to a computer and were used to receive and record both high and low frequency seismic waves. Fast Fourier Transform was used to compute the phase difference based on the signals and was displayed in the cross-power spectrum. The phase information was then unwrapped and analyzed to produce a dispersion curve of phase velocity versus wavelength. Figure 9 shows an example of the composite experimental dispersion curve from the measurements made by all receiver spacings. Subsequent to obtaining the dispersion, inversion analysis was done based on the established theoretical model. In this analysis, the 3-D stiffness matrix model proposed by Kausel and Peek (1982) was used. The final profile of shear wave velocity was obtained after 16 iterations with a root-mean-square error (RMS) of 35.47 m/s or an average deviation of about 5.92 %.

Figure 10 shows the equivalent shear wave profile obtained after inversion while Figure 11 shows the equivalent dynamic elastic modulus profile which was obtained using the dynamic material equation. The modulus profile in Figure 11 is only valid at a depth of 10 cm where the asphaltic layer is located. The elastic modulus shown in the figure is congruent with the elastic modulus obtained when using the WSSW and SASW methods. The difference between the two methods is 0.01 % and 1.14 % for the first and second layer of pavement surface, respectively.

The falling weight deflectometer (FWD) method was used to verify the elastic modulus of pavement surface layer obtained through the WSSW test. Figure 12 shows the elastic modulus of pavement surface layer obtained using both the FWD and WSSW methods. The elastic modulus obtained using WSSW is higher than the value obtained through the FWD test. As mentioned previously, the modulus measured at very low strain levels in the surface wave method is the maximum value, has a high loading frequency, and is not determined by strain amplitude. Contrarily, in the FWD test, the modulus was obtained from backcalculation of in situ measurement of deflection basins. In this test, a falling weight was dropped to obtain a target load of 40 kN in order to generate pavement basins. Nazarian et al. (1999) and Stokoe et al. (1991) reported that the modulus measured in a FWD test usually corresponds with the secant modulus of the materials close to the loading pad (i.e. pavement surface layer and base/subbase layer) and the initial tangent modulus for the materials further from the impact/dropped weight (deeper subgrade). On the contrary, the modulus obtained by using the proposed WSSW method is measured directly using a small seismic source. The modulus thus obtained always corresponds with the initial tangent modulus due to the small impact. This is the reason why the modulus obtained from the proposed WSSW is higher than that obtained via the FWD method. However, as presented in Figure 13, a correlation of data trend from field testing shows that the lower modulus obtained through the FWD method is also measured at lower modulus level when using the WSSW. Additionally, the high frequency of the seismic method generated greater stiffness values for pavement material. Roesset et al. (1990) found that frequency has a significant effect on modulus value at the small strain levels in the seismic and FWD tests. In FWD, modulus was measured at a frequency of approximately 30 Hz (Figure14) calculated from peak frequency of displacement in the auto-spectrum of wave propagation energy recorded by the geophones. This is congruous with the results obtained by Stokoe et al. (1991). These researchers measured the auto-spectrum of the velocity resulting from the impact of an FWD on AC pavement layer. The results of their study show that the impact energy of FWD is concentrated in a frequency range of 2 to 50 Hz with a peak energy of between 25 to 30 Hz. The peak frequency response of FWD obtained in the present study is similar with that obtained by Roesset et al. (1990) where the frequency of FWD was found to be 30 Hz.

Validation with Resilient Modulus Test

In this section, the results obtained via the WSSW test is compared with the result of laboratory resilient modulus (Mr) test conducted at same location of the road pavement on the UKM Campus, Bandar Baru Bangi, Malaysia. WSSW test with identical configuration was conducted at 30 observation points and the data was then processed as described in the previous section. After completing the WSSW test, the specimens of the pavement surface layer to be used for laboratory resilient modulus were cored from the same location. Laboratory resilient modulus, Mr, is the elastic modulus based on recoverable strain under repeated load. The test was conducted in accordance with the ASTM D 4123 under indirect tensile mode using a Universal Testing Machine (UTM). In the resilient modulus test, the time dependent deformation by using constant compressive stress was set up to assess the ability of the cored specimen to recover from repeated loading without reaching failure limit. In this test, the specimens were tested in two orientations, i.e. 0° and 90°. The resilient modulus was computed by assuming a Poisson's ratio of 0.35. A typical result for the resilient modulus obtained from a laboratory test of the sample cored from the road pavement on the UKM campus is presented in Table 1. The AC core was tested at a temperature of 36°C. This temperature is similar with the field temperature when the WSSW test was conducted. Table 1 presents the results for air voids, tensile strain, indirect tensile strength, and resilient modulus test obtained from the measurement of the cored samples of the two testing sites. Statistical analysis of coefficient of variation (CV) and range of acceptance (RA) indicate that the results of resilient stiffness data are statistically sound.

The resilient modulus of all specimens and WSSW tests are presented in Figures 15 and 16. Figure 15 presents the regression analysis of elastic modulus for the resilient modulus test and WSSW test at a surface layer temperature of 36°C. The moduli obtained from the WSSW and laboratory resilient modulus tests are plotted on the *y*-axis and the strain levels obtained from each measurement of the specimens are plotted on the *x*-axis (Figure 16). Similar with the results of the FWD test, the value of elastic modulus obtained from the WSSW test is higher than the value produced by the laboratory resilient modulus test. This difference is due to the different strain levels in both tests. The elastic modulus from the WSSW test is a maximum value and is independent of strain amplitude.

Application of WSSW on Rigid Pavement

In situ Measurement of Elastic Modulus

WSSW measurements were also made on a new rigid pavement in Yogyakarta, Indonesia. The tests were conducted on slabs fabricated using concrete class Type I cement with a maximum aggregate size of 0.019 m. The concrete mixtures for the PCC slab casts were designed to have a minimum 28-day compressive strength of 225 kg/cm^2 (22.04 MPa). The concrete has a cement-water ratio of 0.48 and an average slump of 0.033 m. The 450-mm thick PCC slabs were placed over a compacted layer of sand on subgrade soil. The tests were conducted on the slabs after a curing time of 3, 14, and 28 days.

Figure 17 shows a typical result of time frequency spectrogram of GoD CWT from the measured signals. Signals were recorded with a field measurement configuration of 30 cm receiver spacing (D) on a PCC slab with a 14-day curing time. Figure 17 clearly shows that several signal energy groups at different frequency bands were detected, which could result in interference at low and higher mode of signals. The wave energy events occurred within 0.02 to 0.026 seconds of arrival time (received by accelerometers). It shows that the dominant energy event occurred between 5 to 25 kHz in both signal CWT spectrograms. Within this range, the events were investigated as energy group of surface waves and interference of reflected body waves. The first energy group occurred at a high frequency of between 5 to 16 kHz (channel 1) and 6 to 16 kHz (channel 2), which are identified as surface wave propagation.

The unwrapped raw phase spectrum was then computed and is shown in Figure 18. A linear regression ($y = mx$) of phase angle versus frequency was generated, and the best-fit line has a slope (m) of 0.0535. The phase velocity was calculated based on the slope value and receiver distance using Equation 11 and was found to be 2,018.69 m/s. The unit weight of concrete in the PCC slabs were measured at each elapsed time of the curing process. By assuming a Poisson's ratio and unit weight of concrete material for a 3-day curing time of 0.20 and 2,420 kg/m^3, respectively, the elastic modulus of rigid pavement surface layer were obtained using Equations 13 and 14 and was found to be 23,660.99 MPa (23.66 GPa). Figure 19 shows the measured elastic modulus for concrete PCC slabs at 3-, 14- and 28-day curing time. It shows that WSSW test can also be used to monitor any changes in the stiffness of the surface layer of rigid pavement during the curing of PCC slabs.

Validation with Laboratory Compressive Strength Test

A laboratory compressive test was conducted to validate the value of the stiffness of rigid pavement obtained via the WSSW tests; the test was performed using a standard 6 by 12-in cylinder sample in accordance with compression tests standard ASTM C 39. The compressive tests were conducted to determine the average compressive strength of three cylinders of PCC slab samples. The compression tests were conducted 3, 14 and 28 days after casting. The results for the compressive strengths are presented in Table 2. Figure 12 shows that elastic modulus obtained via the WSSW tests is in good agreement with the compressive strength obtained via the laboratory test with a coefficient of determination of 0.995. This indicates the feasibility of using WSSW to make a quick measurement and predict the elastic modulus of the surface layer (PCC Slab) of rigid pavements.

CONCLUSION

This paper introduces a technique for determining the surface layer stiffness of flexible and rigid pavements by performing a wavelet-spectrogram analysis of surface waves (WSSW). The technique employs a time-frequency analysis of continuous wavelet transforms (CWT) spectrogram to identify energy events, filter the wave modes of interest, and improve the quality of phase spectrogram of the received seismic signals. The technique is also capable of enhancing the transfer function spectrogram used to obtain the phase difference data. By using a simple formulation of phase spectrum slope and material properties of the pavement, the elastic modulus of a pavement surface layer can be determined without having to perform any complex inversion analysis. The WSSW method is a non-destructive test which can be used for regular monitoring of the changes in the elastic modulus of constructed pavement surface and its overlays.

ACKNOWLEDGMENTS

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TABLE

Table 1. Typical result of indirect tensile and resilient modulus tests conducted on the sample of AC cored from a pavement-road on the UKM Campus, Malaysia

Sta	Sampel No.	Air Voids (%)	με (tensile)	σ (tensile)	M_R (MPa)
0+200	A-1	5.06	118.90	211.90	1735
0+200	A-2	5.32	120.10	214.60	1739
0+200	A-3	4.89	148.10	261.70	1720
	Mean	5.09	129.03	229.40	1731
	SD*				10.02
	CV*				0.58%
	RA*				1.64%

Sta	Sampel No.	Air Voids (%)	με (tensile)	σ (tensile)	M_R (MPa)
0+300	B-1	4.65	84.44	2070	2388
0+300	B-2	5.12	85.03	204.50	2343
0+300	B-3	4.64	85.63	203.30	2312
	Mean	4.80	85.03	204.90	2347
	SD*				38.21
	CV*				1.63%
	RA*				4.61%

Table 2. Average compressive strength of PCC slabs of a new rigid pavement after varying curing time

Elapsed time (curing period) in days	No. PCC Slabs Sample Test	Average Elastic Modulus from WSSW Test (MPa)	Average compressive strength of PCC Slab (MPa)
3	1	23,660	14.2
	2	22,980	14.6
	3	23,420	13.9
14	1	31,130	25.0
	2	30,760	24.3
	3	31,250	24.9
28	1	33,560	28.3
	2	34,070	28.9
	3	33,810	27.9

Figure 1 Click here to download Figure Figure 1.pdf

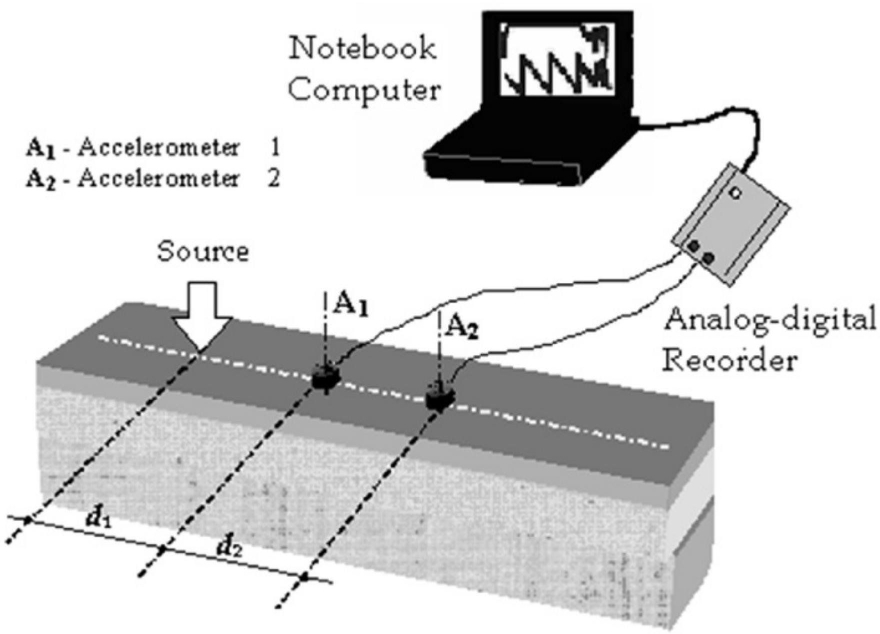

Figure 1. Experimental set up for WSSW measurement on a pavement structure

Figure 2 Click here to download Figure Figure 2.pdf

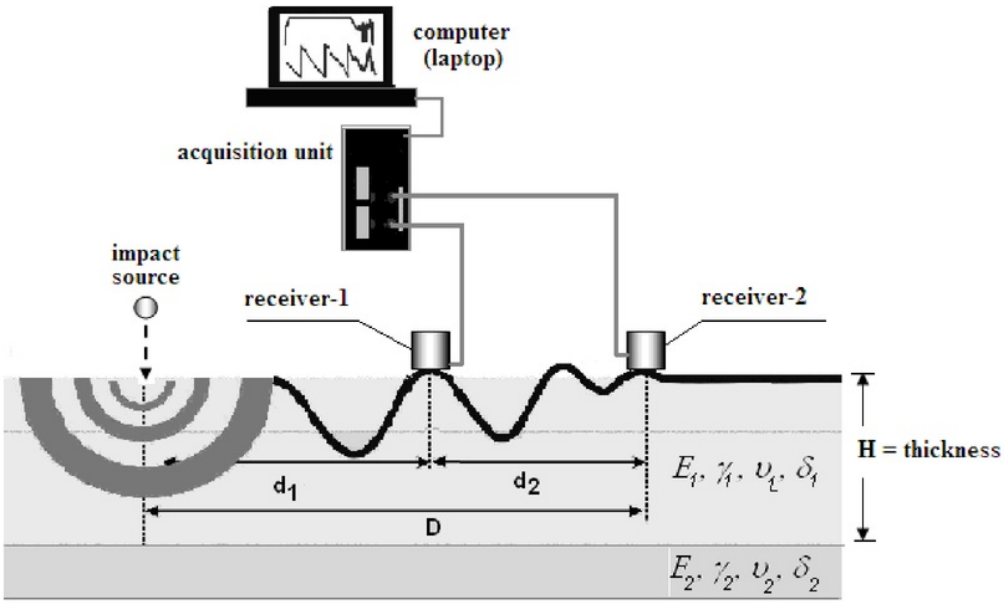

Figure 2. Mid-point receiver configuration for WSSW measurement on pavement structure

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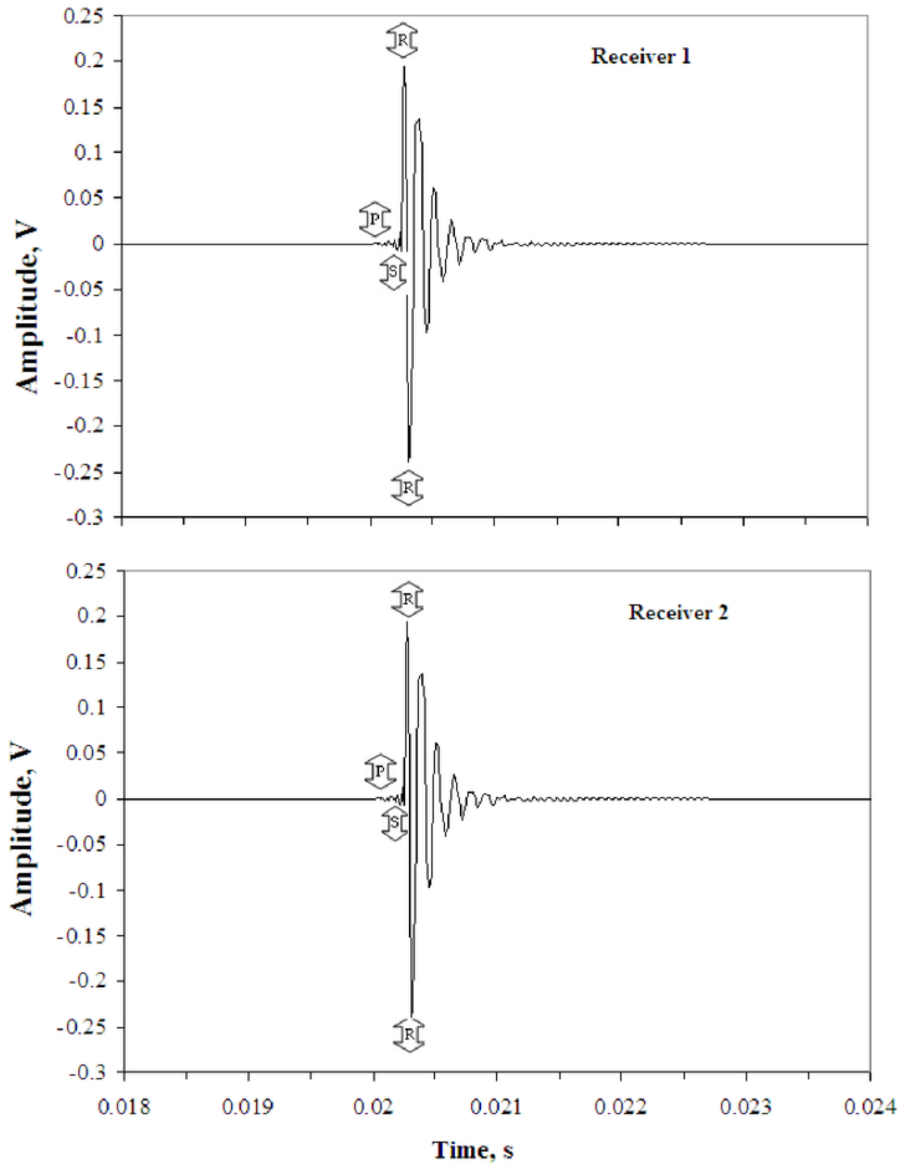

Figure 3. Typical signals from WSSW measurement on a pavement structure

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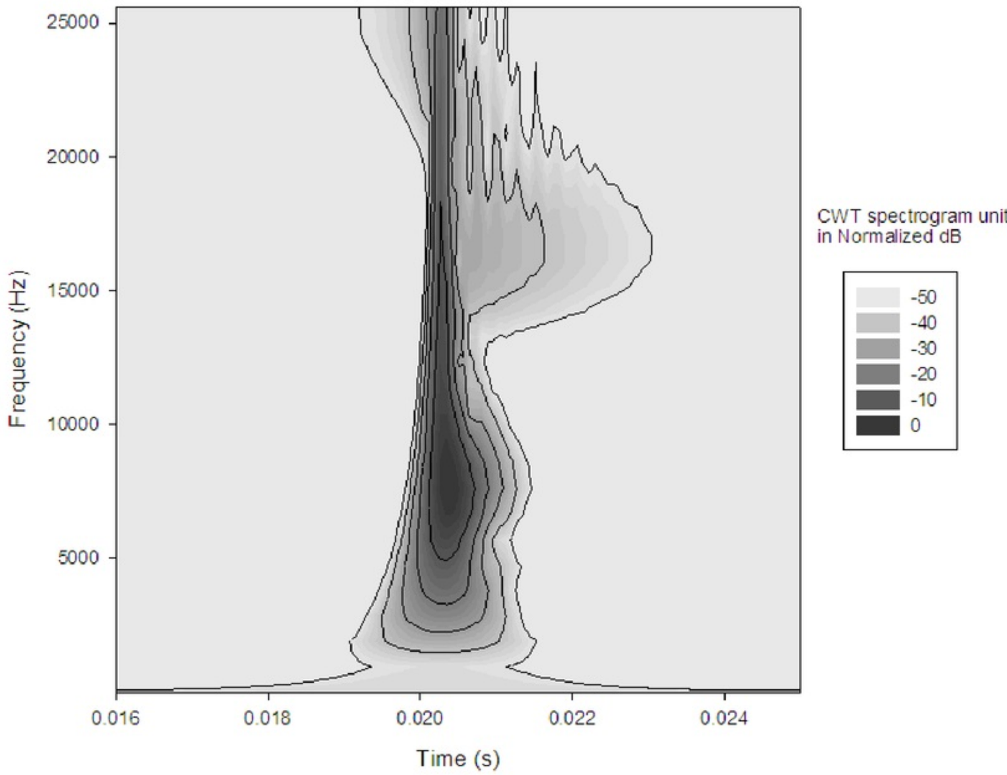
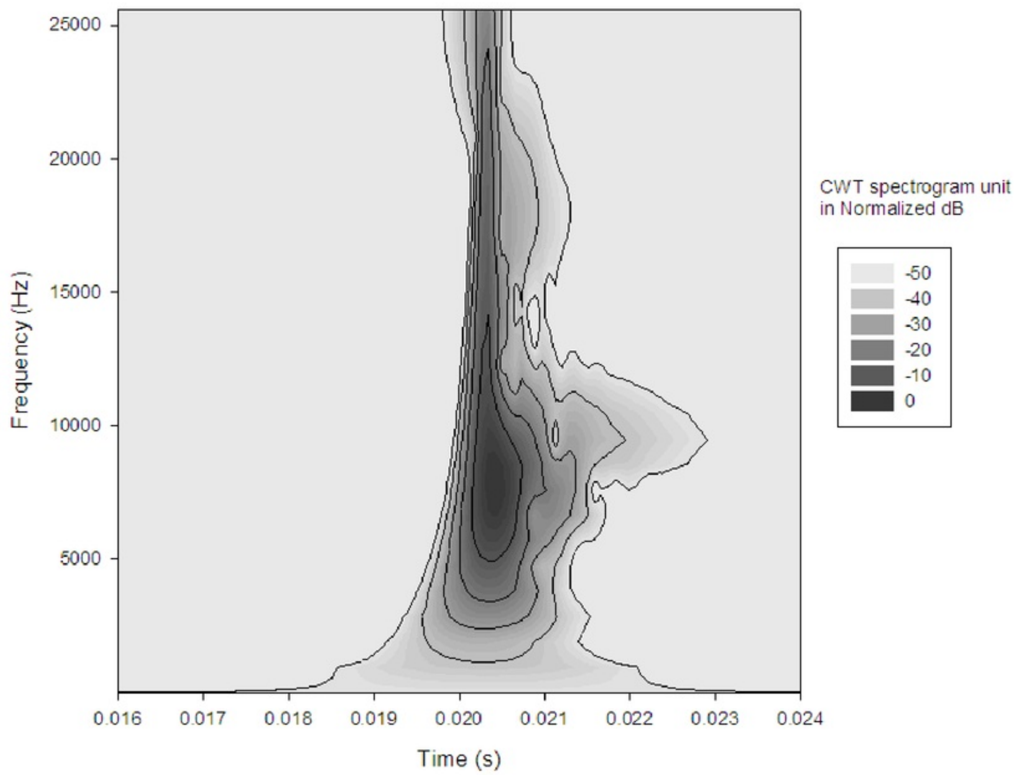


(a) CWT Spectrogram displayed in normalized-dB energy amplitude distribution from receiver 1



(b) CWT Spectrogram displayed in normalized-dB energy amplitude distribution from receiver 2

Figure 4. Time-frequency plot of received signals from WSSW measurement at national road pavement site in Purwakarta, Indonesia

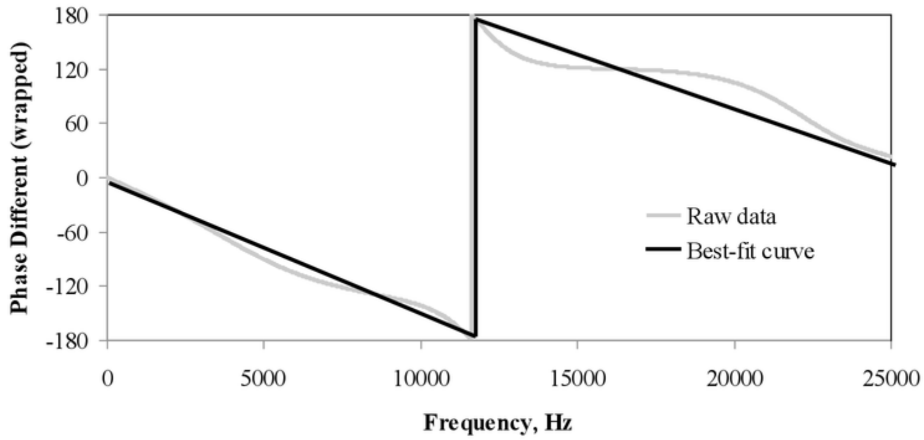


Figure 5. Comparison of raw data and best-fit curve of wrapped transfer function spectru based on measurements

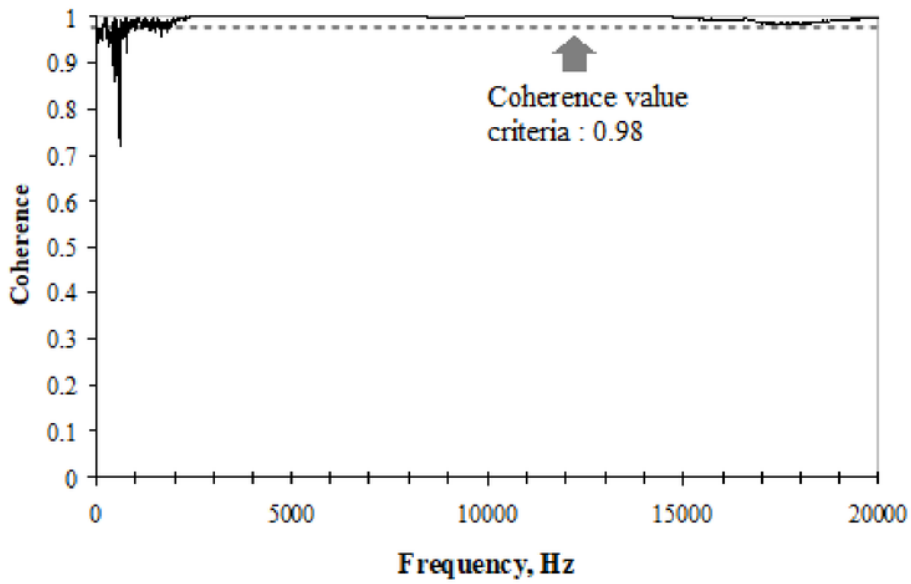


Figure 6. Coherent function spectrum of received signals from measurement

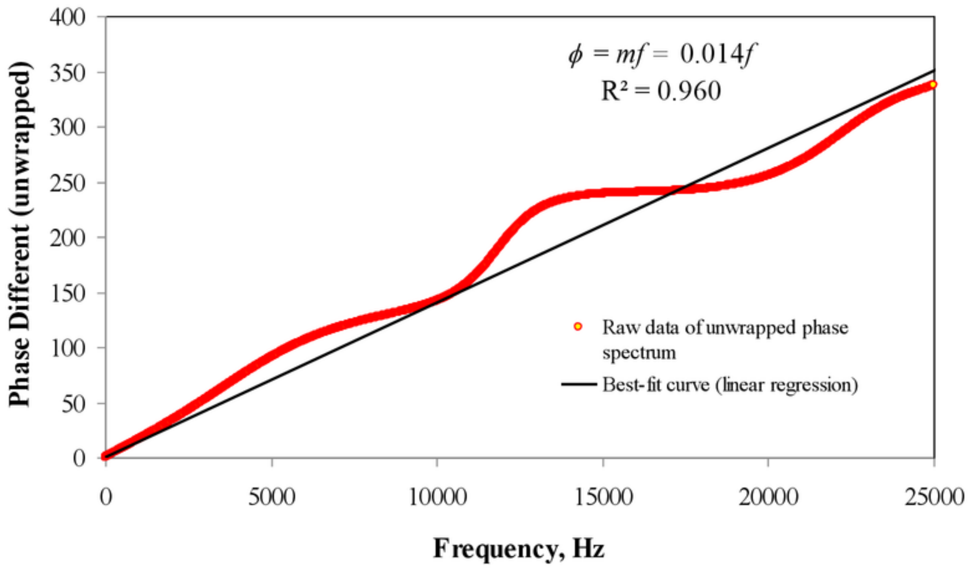


Figure 7. Linear relationship of phase difference and frequency in the unwrapped transfer function for obtaining the slope (*m*) parameter at flexible pavement site in Purwakarta, Indonesia

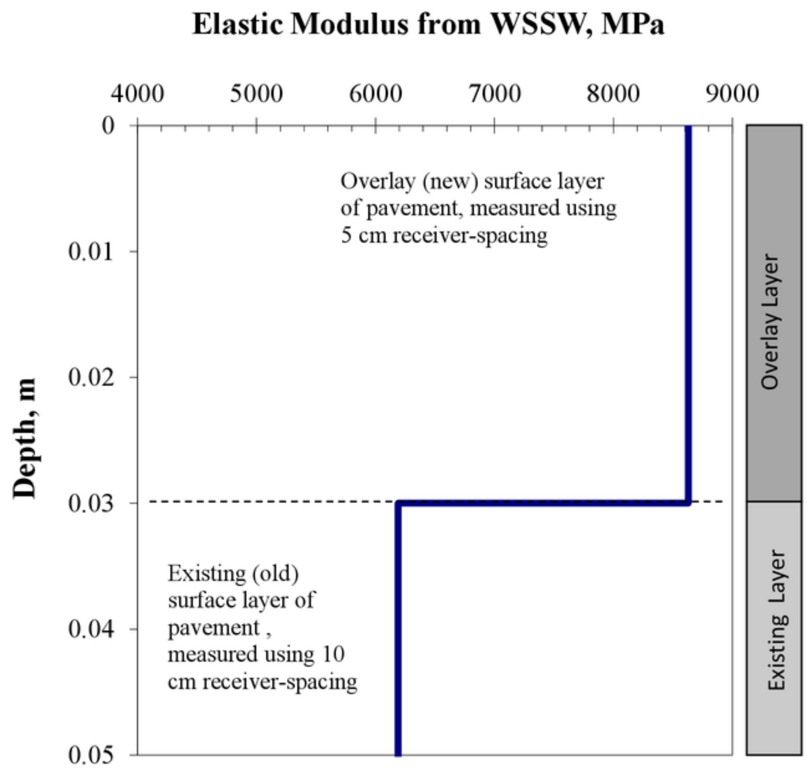


Figure 8. Elastic modulus profile of pavement obtained using the WSSW method for an overlay and existing surface layer of a flexible pavement test site at Purwakarta, Indonesia

Figure 9 Click here to download Figure Figure 9.pdf

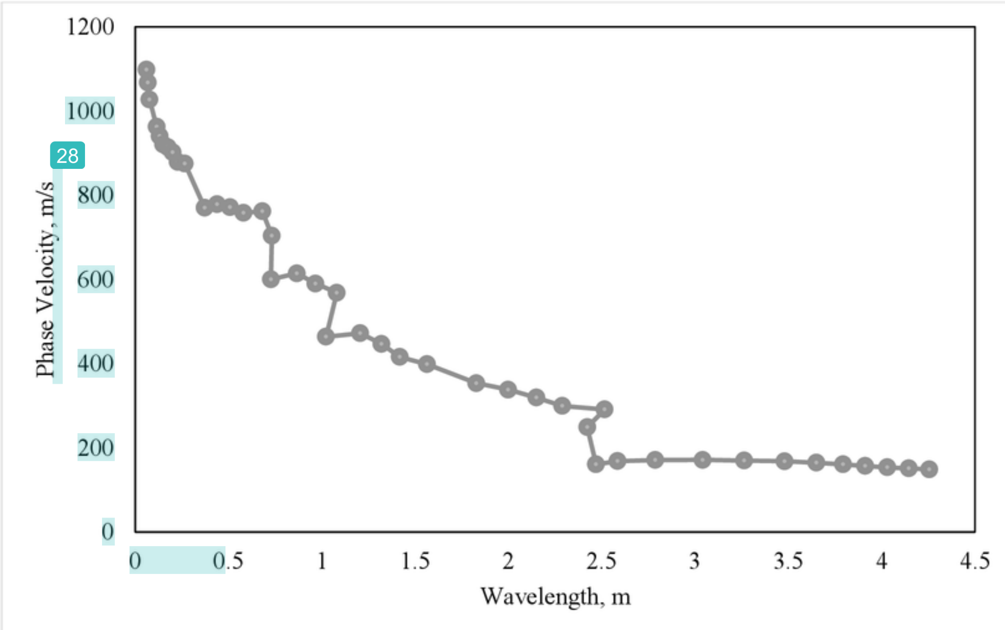


Figure 9. Example of a typical dispersion curve for SASW tests conducted on the Cikampek Purwakarta pavement road, Indonesia showing the variation in wavelength and phase velocity

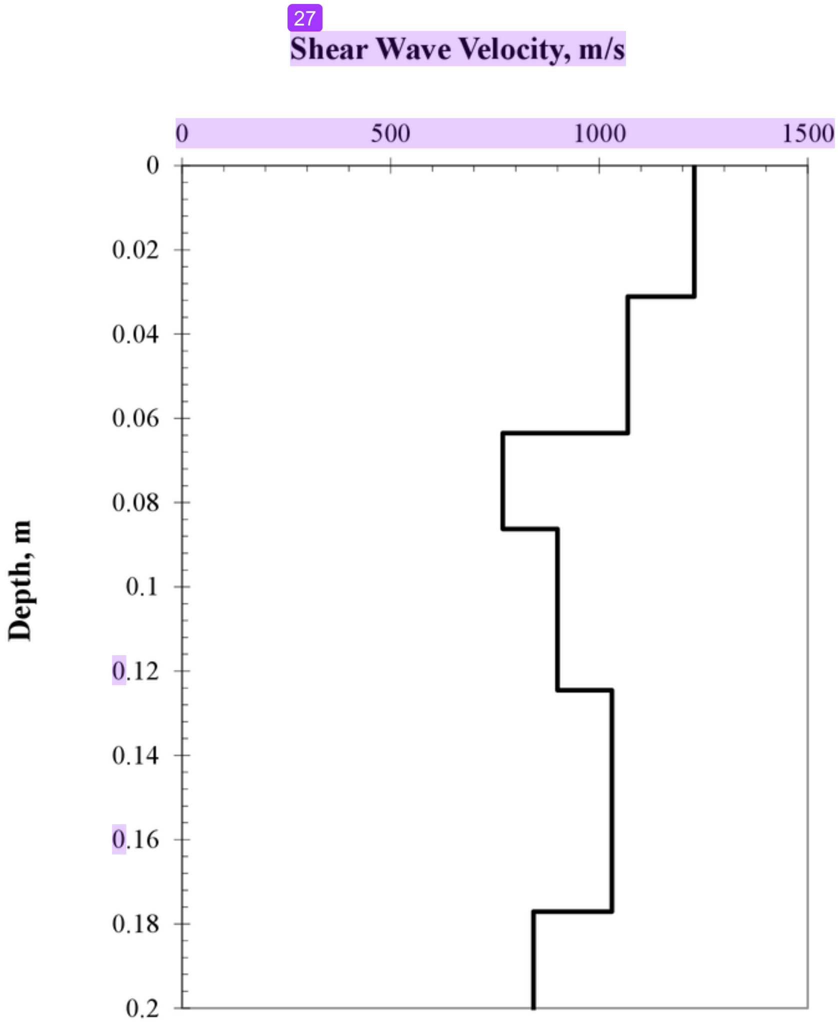


Figure 10. Shear wave velocity profile from inversion of an experimental dispersion curve measured using the SASW test on a national road network in Purwakarta, West Java, Indonesia

Figure 11 Click here to download Figure Figure 11.pdf

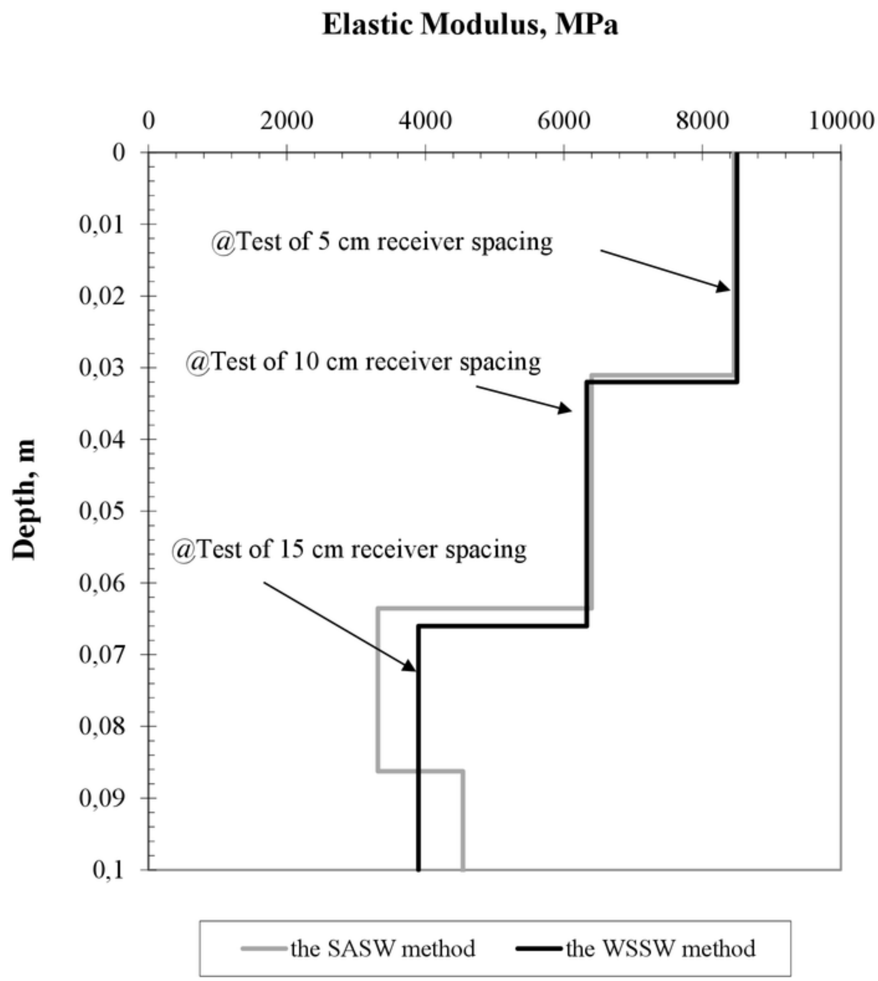


Figure 11. Dynamic elastic modulus of pavement profile obtained using the SASW method in comparison to that of the WSSW method

Figure 12 Click here to download Figure Figure 12.pdf

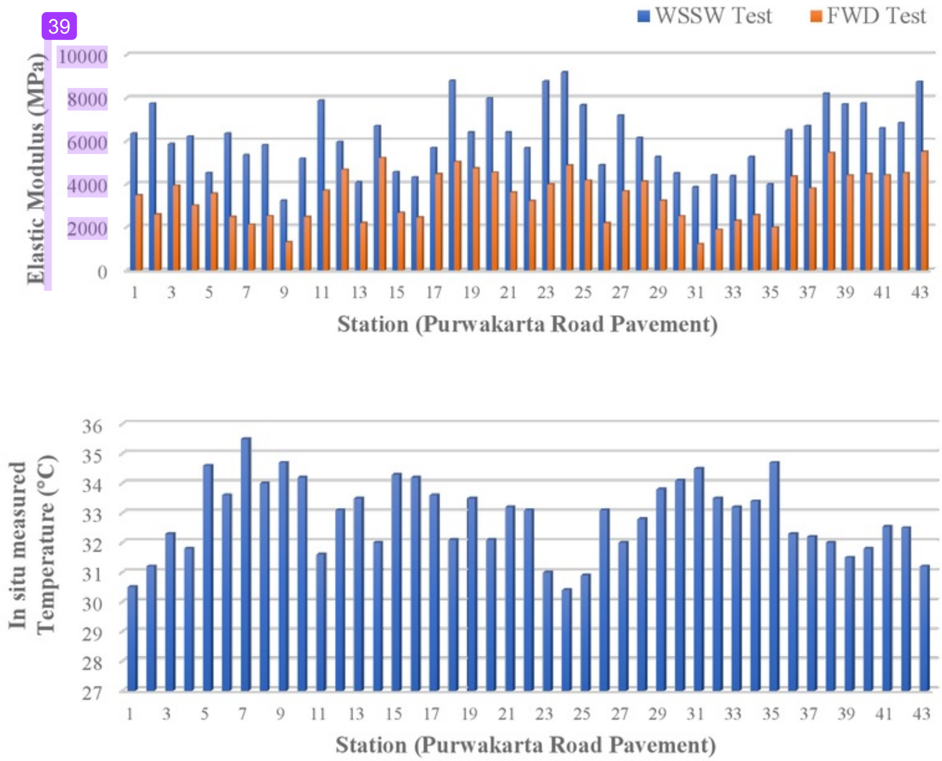


Figure 12. Comparison of elastic modulus of surface layers for a a national road in Purwakarta, Indonesia obtained using the SASW and FWD tests

Figure 13 Click here to download Figure Figure 13.pdf

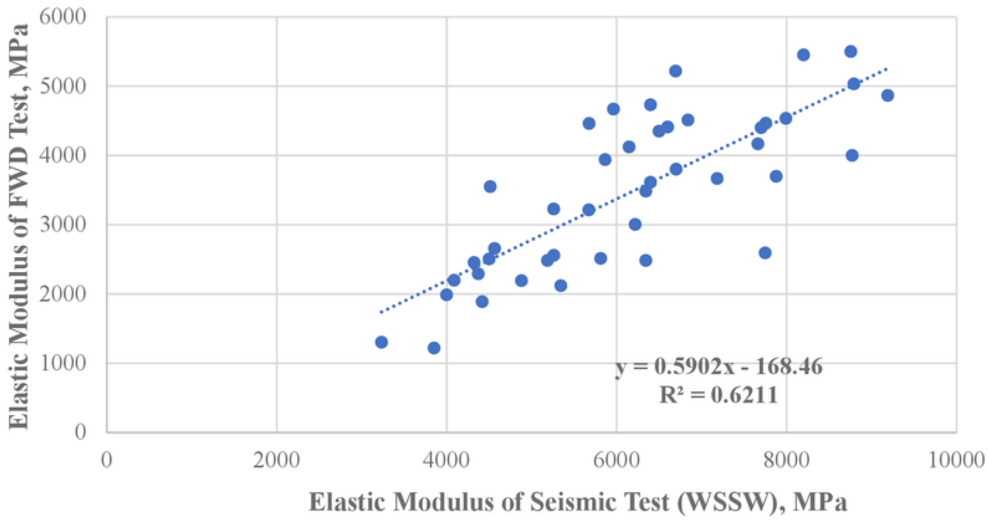


Figure 13. Linear regression analysis and data trendline of elastic modulus of surface layers from the WSSW test and FWD test on a national road in Purwakarta, Indonesia

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Figure 14 Click here to download Figure Figure 14.pdf

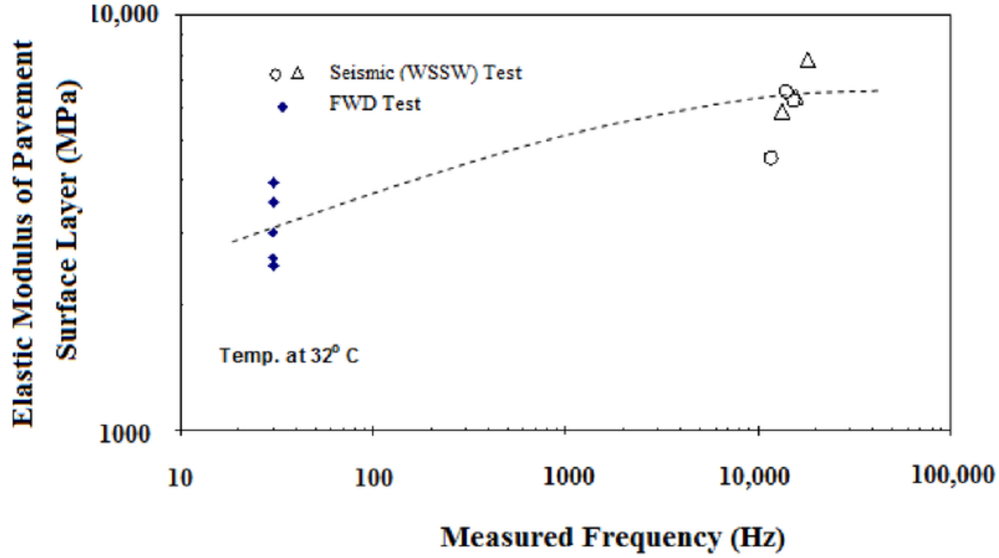

Figure 14. Comparison of the effect of loading frequency on a small strain elastic modulus of an asphalt concrete in Purwakarta, Indonesia obtained from FWD and WSSW tests conducted at a temperature of 32° C

Figure 15 Click here to download Figure Figure 15.pdf

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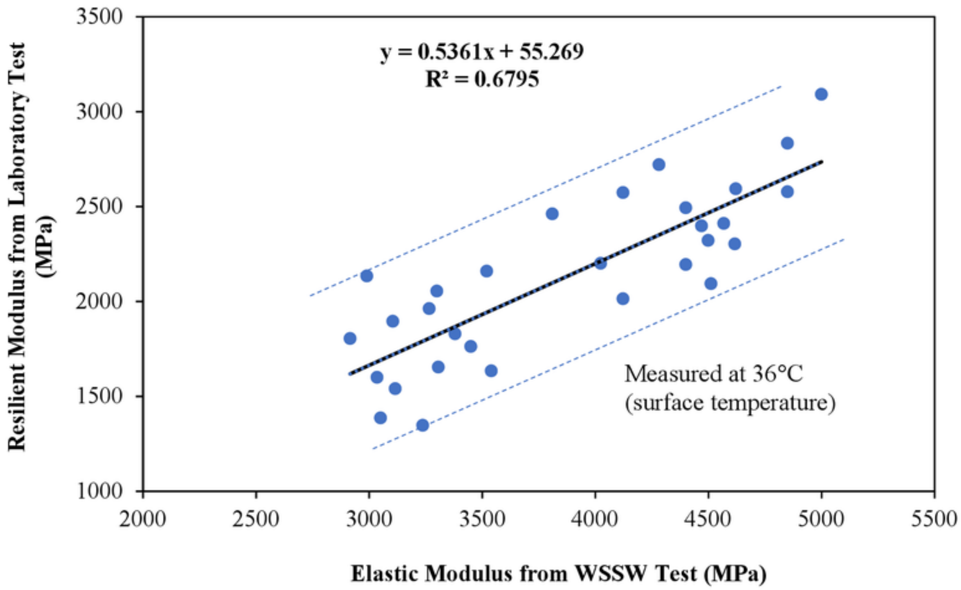

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Figure 15. Regression analysis on elastic modulus obtained from the WSSW test and laboratory resilient modulus on road-pavement at the UKM Campus, Malaysia

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Figure 16

Click here to download Figure Figure 16.pdf

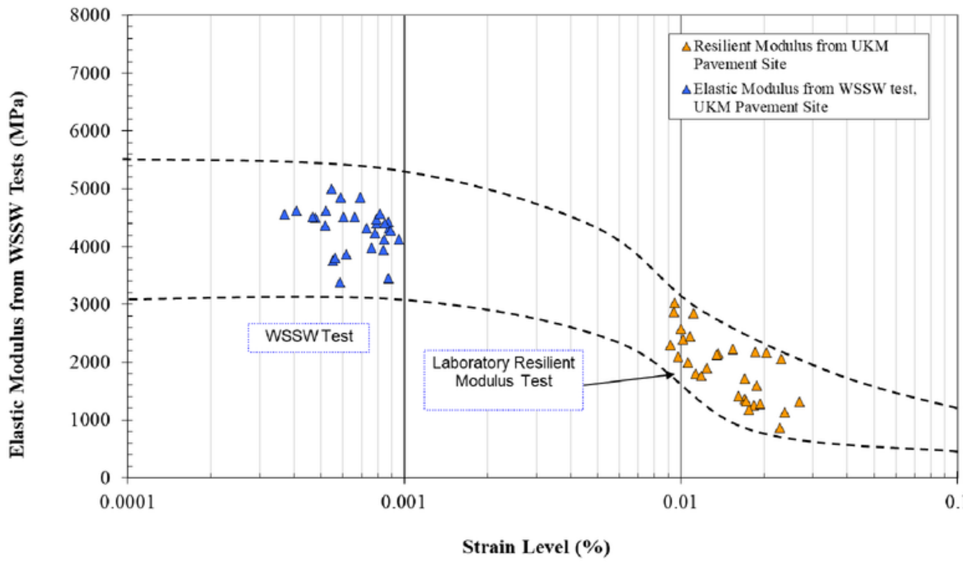
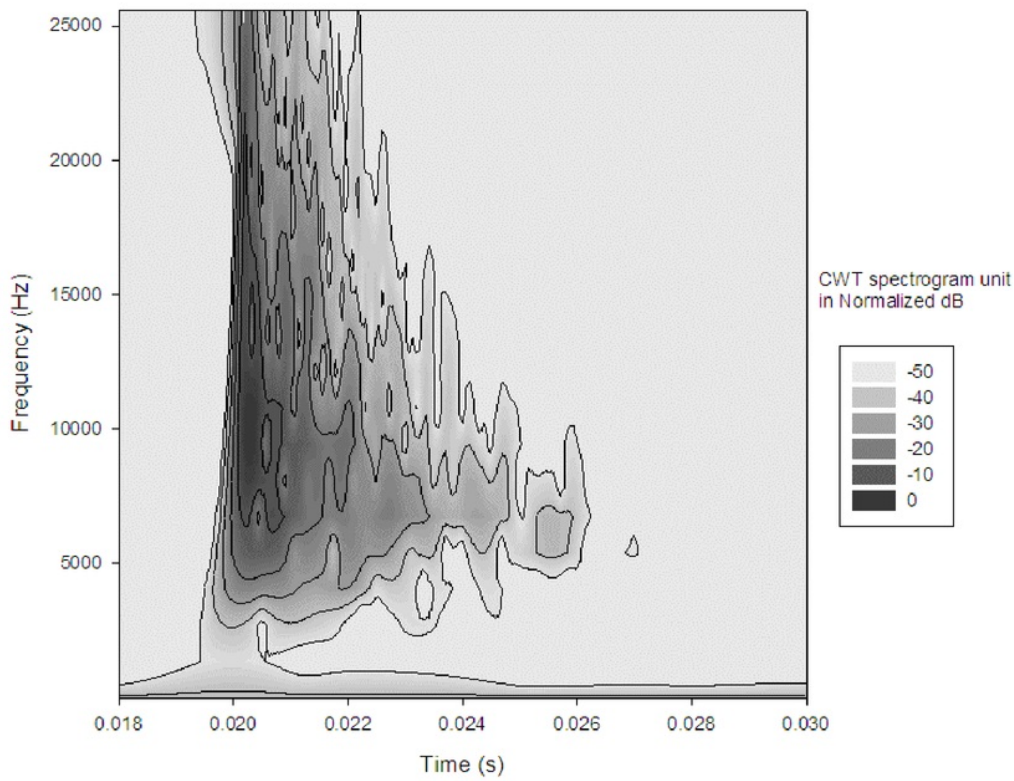
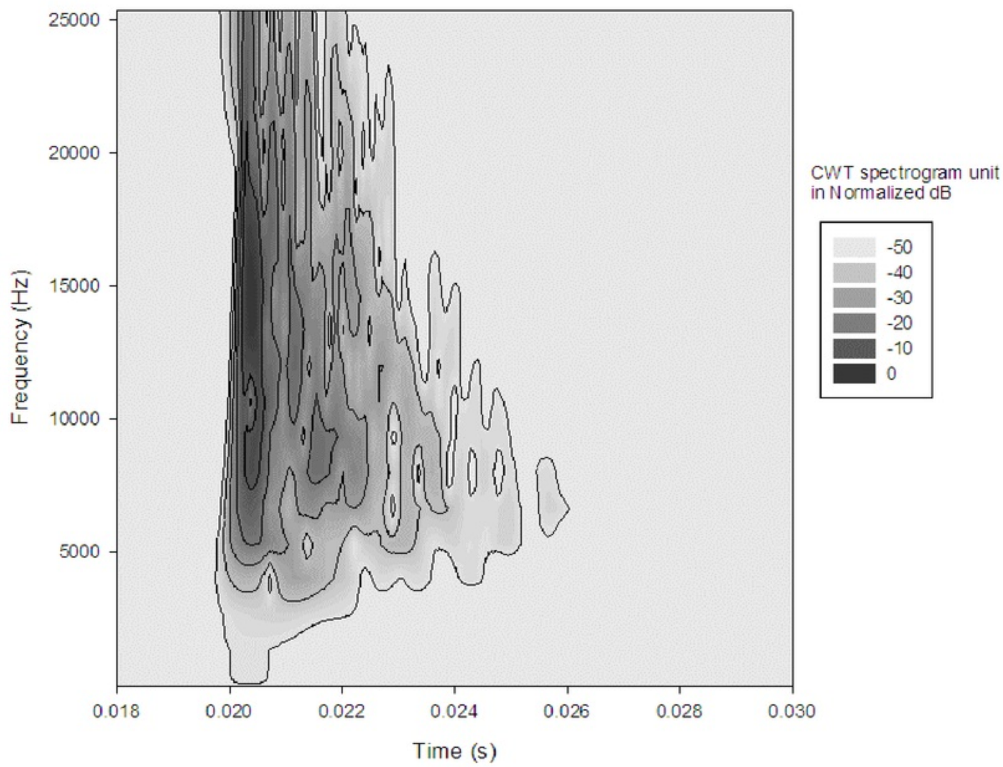


Figure 16. Comparison of elastic modulus obtained using the WSSW test and laboratory resilient modulus obtained through the Indirect Tensile Test on existing flexible pavement on the UKM Campus, Malaysia



(a). CWT Spectrogram for receiver 1



(b). CWT Spectrogram for receiver 2

Figure 17. Time-frequency plot of received signals from field measurement of rigid pavement in Yogyakarta, Indonesia

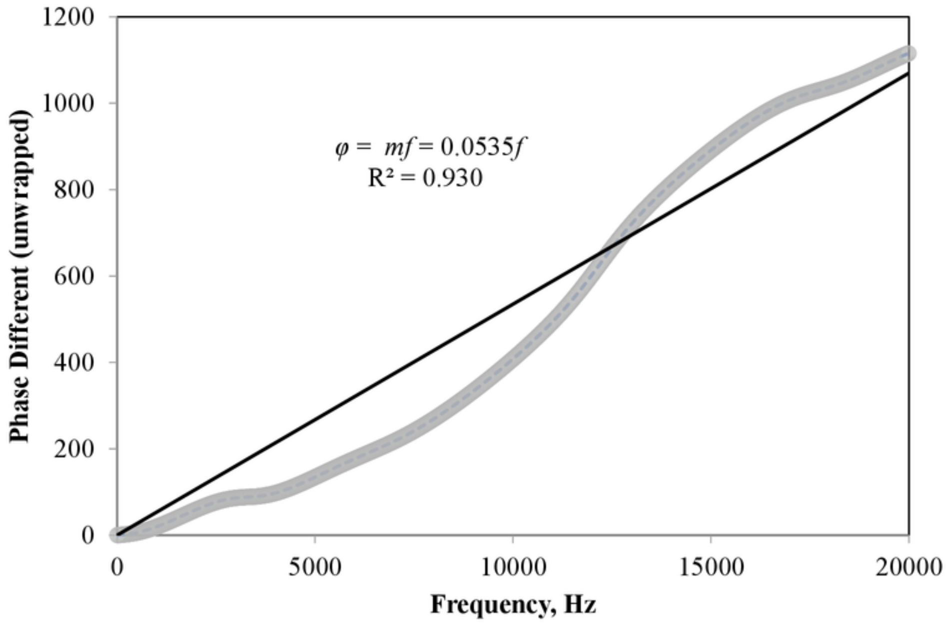


Figure 18. Linear relationship of phase difference and frequency in the unwrapped transfer function for obtaining the slope (m) parameter at rigid pavement site in Yogyakarta, Indonesia

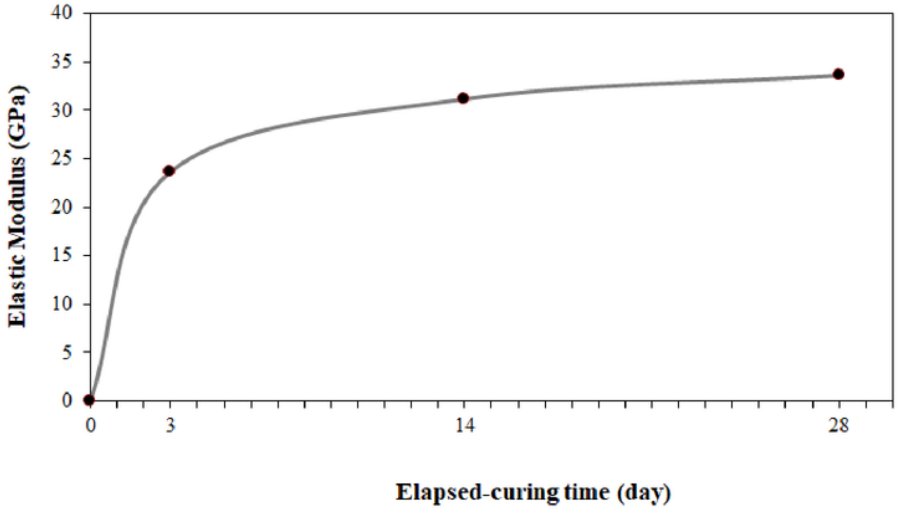


Figure 19. Stiffness monitoring at various elapsed-curing time using the WSSW test on rigid pavement sites

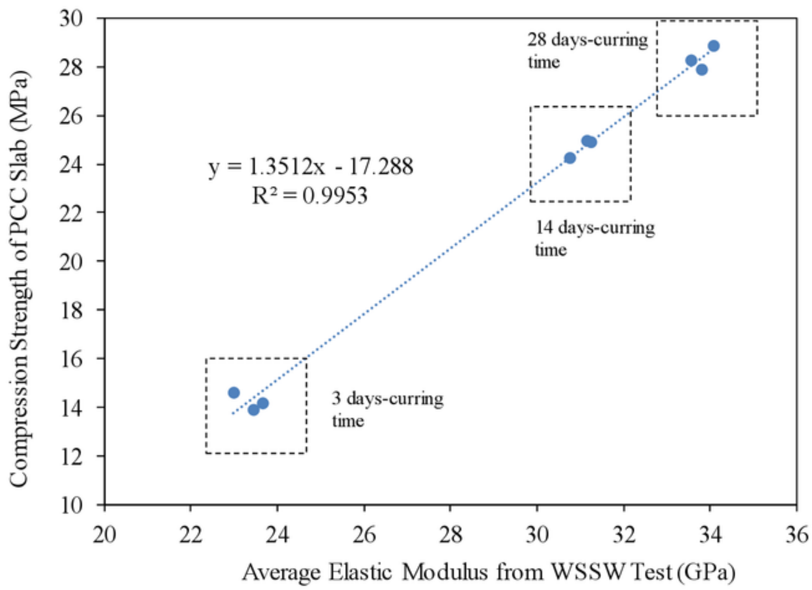


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Figure 20. Comparison of average elastic modulus obtained through the WSSW test and laboratory compression strength of PCC slabs for rigid pavements with different curing time

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Figure 20. Comparison of average elastic modulus obtained through the WSSW test and laboratory compression strength of PCC slabs for rigid pavements with different curing time

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13 The authors wish to thank the editors and reviewers for their time in effort in reviewing our manuscript. We hope the changes listed have made the manuscript 13 suitable for publication and we look forward to your response.

Editor Comments	Author's Response
Your Technical Paper, listed above, has completed a review for publication in ASCE's Journal of Materials in Civil Engineering. The editor has requested that minor revisions be made based on the reviewers' evaluations (shown at the end of this email) and submitted for re-review by 03/02/2018. This revision will only be seen again by the editor and will not undergo the entire review	Authors would like to thank you for the comments from the editor and reviewers. The suggested correction has been made based on the reviewers' evaluation.

Reviewer 2's Comments	Author's Response
The paper is suitable for technical note. However, after addressing following comments. 1. The paper still needs improvement in English and grammar	We would like to thank you for the manuscript review in the English and grammar for improving our manuscript. The correction has been made on the manuscript. An English proofreading was also conducted by professional English proofreader.
2. Figure 14 values look on higher end. Are they realistic particularly at 32 C?	Authors would like to thank you for the comments. We have double check in data and analysis of WSSW test which show that the the elastic modulus of asphaltic materials obtained in the result are rea 38 ic.It was also in the acceptable range of elastic modulus for AC materials as reported by Stokoe et al. (1991), Nazarian et al. (1991). In Figure 14, the seismic testing uses the high frequency which produces higher modulus compared to FWD. In addition, the results of elastic modulus from WSSW and compared results from FWD in Figure 14 are also presented in Figure 13 with various temperature observation. We reported the elastic modulus in the y-axis with logarithmic scale.
3. The compression strength of PCC slabs for reported in Figure 20, is not seems to be incorrect. Please check	We would like to thank you for correction on the compressive strength. The correction has been made. The corrected value of compressive strength (in MPa) was reported in

	Figure 20.

Reviewer 3's Comments	Author's Response
The comments were properly addressed and the paper is ready to be published.	25 The authors wish to thank the reviewer for their time in effort in reviewing, correcting and giving the feedback on our manuscript.

Thank you again for your time and effort, and for helping us improve the manuscript.

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