Characterization of In Situ Modulus of Asphalt Pavement and Its Relation to Cracking Performance Using SASW Method

Xue Wang[1]; Hai Huang[2]; Shihui Shen, A.M.ASCE[3]; Guanglai Jin[4]; Quan Mao[5]; and Haizhu Lu[6]

Abstract: Asphalt material is generally characterized by the modulus, whose change and decay under the same condition could be considered an indicator of pavement performance deterioration. A nondestructive seismic method, the spectral analysis of surface waves (SASW), has been developed for assessing the in situ elastic modulus of the pavement material, which has some unique advantages compared to other methods. This study presents two case studies to evaluate the attenuation characteristics of the in situ modulus of asphalt pavement using the seismic-based SASW method and relate the reduction in modulus with pavement cracking performance. An accelerated pavement testing (APT) using an MLS66 facility study was first conducted on a newly constructed semirigid asphalt pavement test section to evaluate the attenuation of pavement modulus under accelerated loading. The SASW method was used to develop the characteristic dispersion curves for localized pavement sections and obtain the elastic modulus of each layer in different directions after the inversion analysis. In the second case study, the relationship between the modulus properties and the cracking distresses of the pavement was developed. It was found that the overall trend of modulus attenuation in the asphalt layer can be divided into four stages. The trends of variation were different in each asphalt layer and in different directions, which can be used to relate to damage occurrence. The modulus measured in the longitudinal direction was considered to be a better indicator of pavement deterioration in asphalt layers. In addition, based on the case study results, it was suggested that the potential modulus reduction rate for crack occurrence was approximately 40%–50%, which was consistent with the laboratory fatigue criterion of 50% initial modulus reduction. This study confirmed the feasibility of using SASW testing to monitor the attenuation of in situ pavement modulus and predicting impending cracks in specific asphalt layers. **DOI: 10.1061/JPEODX.0000195.** © *2020 American Society of Civil Engineers.*

Author keywords: Spectral analysis of surface wave (SASW); Pavement evaluation; Nondestructive testing; Dispersion curve; Modulus.

Introduction

Maintaining sufficient load bearing capacity is one of the most important goals of asphalt pavement. There are three main ways to estimate the load bearing capacity of asphalt layers, i.e., the mechanistic-empirical model, the AASHTO structure number method, and the deflection measurement, all of which need to evaluate the characteristics of the modulus of the asphalt layer (Zhao 2015). Modulus attenuation has been found to relate to cracking performance and is a reflect of the pavement damage (Mobasher et al. 1998; Svasdisant et al. 2002; Timm and Priest 2008). Laboratory tests such as the 4-point bending beam fatigue test for asphalt mixture and the linear amplitude sweep (LAS) test for asphalt binder were conducted to establish a quantitative correlation between modulus reduction and fatigue cracking (Hasaninia and Haddadi 2018; Hintz and Bahia 2013; Zofka et al. 2017). In a controlled strain loading mode, 50% initial modulus reduction was considered as a reasonable and convenient criterion to define fatigue failure; however, cracking was usually not visible in specimens (Lee et al. 2000; Shen and Lu 2010; Yang 2007).

At present, there are two main methods to estimate the modulus in the asphalt pavement: direct experimental measurement on field cores and on-site nondestructive testing (NDT). The direct measurement method was to extract some core samples from the field and perform a laboratory dynamic modulus test. The obtained modulus was then treated as the modulus of the pavement layer. Although straightforward and easy to control, there were several disadvantages of the direct measurement method: (1) coring was destructive and could damage the pavement; (2) laboratory loading and boundary conditions were different from the field; and (3) it was very difficult to obtain the modulus attenuation trend throughout the pavement service life (Ellis 2008). Therefore, NDT methods became popular alternatives due to being able to evaluate the material characteristics without damaging the pavement, and having

[1]Ph.D. Candidate, Key Laboratory of Road and Traffic Engineering of the Ministry of Education, College of Transportation Engineering, Tongji Univ., Shanghai 201804, China. ORCID: https://orcid.org/0000-0002-9493-882X. Email: iswangxue@tongji.edu.cn

[2]Associate Professor, Dept. of Engineering, Penn State Univ., Altoona, PA 16601. Email: huh16@psu.edu

[3]Associate Professor, Penn State Altoona, Altoona, PA 16601; Adjunct Professor, Key Laboratory of Road and Traffic Engineering of the Ministry of Education, College of Transportation Engineering, Tongji Univ., Shanghai 201804, China (corresponding author). Email: szs20@psu.edu; sshen2@tongji.edu.cn

[4]Deputy Director, Jiangsu Sinoroad Engineering Technology Research Institute Co. Ltd., 99-196 Taizhong Rd., Nanjing, Jiangsu 211806, China. Email: jgl@sinoroad.com

[5]Deputy Director, Jiangsu Expressway Engineering Maintenance Technology Co. Ltd., 168 Tianyuan West Rd., Jiangning District, Nanjing, Jiangsu 211100, China. Email: 13952038445@139.com

[6]Deputy Principal Engineer, Jiangsu Highway Engineering Maintenance Technology Co. Ltd., 168 Tianyuan West Rd., Jiangning District, Nanjing, Jiangsu 211100, China. Email: 18851125135@163.com

Note. This manuscript was submitted on March 27, 2019; approved on February 11, 2020; published online on May 12, 2020. Discussion period open until October 12, 2020; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Transportation Engineering, Part B: Pavements***, © ASCE, ISSN 2573-5438.

higher efficiency, low cost, environmental friendliness, and reliability (ASTM 2003).

NDT methods can be classified according to fundamental principles into deflection-based methods like falling weight deflectometor (FWD) and traffic speed deflectometer (TSD), and seismic-based methods like spectral analysis of surface waves (SASW). Currently, the State Departments of Transportation of the United States regards the FWD as a standard method to determine the elastic modulus of layered asphalt pavement (Aouad et al. 1993b). However, the back-calculation procedure in the FWD method requires some unknown information such as the thicknesses of each layer and is insensitive to the change of the modulus in surface layer (Alexander et al. 1989; Tarefder and Ahmed 2013). The back-calculated layered modulus may be different depending on the initial values selected and the methodology used. Such shortcomings can significantly reduce the accuracy and reliability of the measured results of elastic modulus in asphalt pavement. On this foundation, the SASW method was developed in the early 1980s based on the generation and detection of Rayleigh waves (Nazarian and Stokoe 1983, 1984, 1985). In the SASW method, the shear-wave velocity profile variation with depth was evaluated from the dispersion curve, a plot of velocity versus wavelength or frequency, by the inversion analysis; the modulus profile can thus be determined based on the shear-wave velocity profile (Kumar and Naskar 2015; Stokoe et al. 2004). Because the SASW method mainly obtains the information through the Rayleigh wave whose propagation depends on the characteristic of material itself, the modulus calculated from the shear-wave velocity is relatively unique. Compared to other NDT methods such as the FWD, the SASW method had three major advantages including: (1) the thicknesses of the various layers can be calculated from the iterative inversion of the dispersion curve; (2) the modulus of the shallow pavement layer can be accurately measured through the high frequency waves; and (3) the modulus of each layer can be calculated separately and uniquely. It is worth noting that the SASW method also has some disadvantages that can prevent it from being more widely used in the practical field. For instance, the complex inversion analysis requires professional knowledge and engineering experiences, and the efficiency of the testing and data processing is relatively low. Further research is strongly encouraged in these areas.

Because the SASW method was developed, it has been applied by many researchers to determine the elastic modulus of asphalt, base, and subgrade layers (Ismail et al. 2012; Ryden 2009; Terrell et al. 2003). Rosyidi (2004) used the SASW method and dynamic cone penetrometer (DCP) to assess the stiffness parameters of the subgrade layer, and developed the empirical relationship between the DCP value and the soil elastic modulus. Based on Rosyidi's research, Widodo et al. (2009) used the modulus of subgrade from SASW method to predict its bearing capacity. In the measurement of asphalt layer modulus, Nazarian's research team conducted extensive field experiments to illustrate the accuracy and applicability of the SASW method (Nazarian and Stokoe 1986, 1984, 1985). In order to monitor the long-term performance of in-service pavement, a series of SASW tests were conducted to evaluate the modulus attenuation of asphalt pavement over a period of time (Aouad et al. 1993a; Storme et al. 2004). The SASW method was also combined with APT testing to study the pavement performance deterioration trend under controlled traffic and environmental conditions (Lee et al. 1997; Walubita et al. 2000). It was found that the effect of moisture damage and cracking can both result in clear modulus attenuation. However, these studies were conducted on existing pavements that had been in service for several years. They were unable to obtain the complete modulus attenuation trend, which was critical for making pavement maintenance decisions. In addition, most existing researches only focused on the modulus of the whole asphalt layer and paid less attention to the different deterioration trends along the depths of the asphalt layer. Understanding the different behaviors of different asphalt layers should provide insight into the perpetual pavement design concept.

In summary, the SASW method was believed to be a feasible and reliable nondestructive technique to characterize the modulus of pavement throughout the service life of pavement (Popovics and Abraham 2010). Its unique capability of obtaining the fundamental dispersion characteristics of each asphalt layer allowed it a more precise quantification of the in situ modulus and correlated it with pavement performance. However, its effectiveness on semirigid base pavement has not been evaluated yet and existing studies have not provided quantitative correlation between modulus attenuation and cracking performance deterioration. Therefore, the objectives of this study are to evaluate the attenuation characteristics of in situ modulus of asphalt pavements through two case studies and relate the change of modulus behavior with pavement cracking performance using the seismic-based SASW method.

Methodology and Scope

To research the characteristics of the in situ modulus of semirigid asphalt pavement and its relation to cracking performance, this paper was performed based on two case projects: an APT test using MLS66 facility study was first conducted to evaluate the change of pavement modulus under accelerated loading. Under a well-controlled loading condition, the general trend of modulus attenuation under traffic loading was developed. Then an in-service pavement was analyzed to explore the relationship between modulus properties and pavement cracking distresses. The SASW method, an on-site nondestructive testing method, was used to develop the characteristic dispersion curves for localized pavement sections and obtain the elastic modulus of each layer in different directions after the inversion analysis. Based on the SASW analysis results, the anisotropic behavior of asphalt layered modulus and the attenuation rate of modulus for crack occurrence were discussed.

Theory of SASW Method

Field Arrangement

This study used an Olson Instruments (Wheat Ridge, Colorado) NDE-360 Platform for SASW measurement, which consisted of an impact source, two receivers placed vertically in a line, and a dynamic signal analyzer with an anti-aliasing filter, as shown in

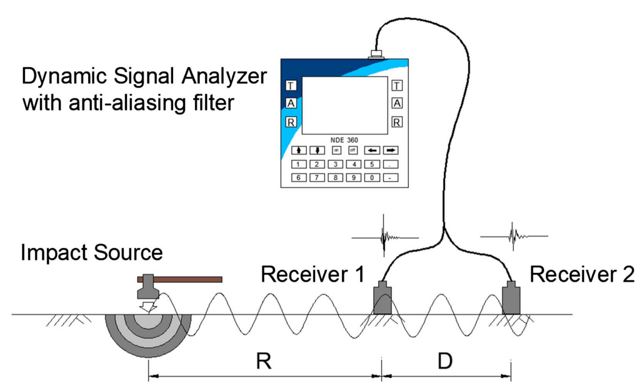

Fig. 1. Basic configuration of equipment for SASW measurements.

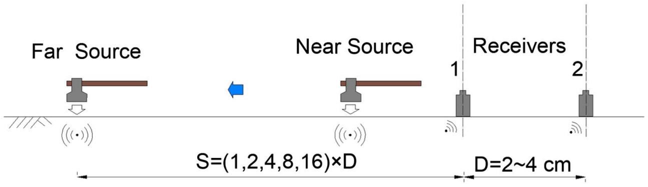

Fig. 2. SASW measurement layout.

Fig. 1. In the NDE-360 platform, data sampling rate means how often the system will acquire data points within a given data trace in the time domain, which is generally set as a 20-ms interval per data point in this research. The total points per record are usually set as 1,024. Therefore, the duration of signal in a time domain is about 7,168 ms, and the frequency content of the signal can be up to 7,000 Hz. During the measurement, the distance between the source and near receiver (R) was increased to multiple times (such as 2, 4, 6, and 8) of the distance between the two receivers (D) following a common array profiling (CAP) method, as shown in Fig. 2. Both forward and reverse profile measurements were conducted for each receiver array, which can eliminate the influence of any unexpected internal phase shifts correlated with the receivers or the signal analyzer (Aouad et al. 1993b). The reverse profile measurement referred to perform a test from the opposite sides of the receiver array of the forward profile measurement.

Spectral Analysis of Surface Wave

The SASW method relies on generating and measuring Rayleigh wave to obtain the stiffness profile of pavement structure (Heisey et al. 1982). Because the Rayleigh wave propagates along the surface or interface layer and will not lose much energy over a large offset range, it is very suitable for measuring layered material (Hazra and Kumar 2014). Compared to other types of wave, the Rayleigh wave has lower velocity, lower frequency, and higher amplitude. In a heterogeneous world, the Rayleigh wave is dispersive. The Rayleigh wave of low amplitude and high frequency (shorter wavelength) penetrates shallower layers, whereas a wave of high amplitude and low frequency (longer wavelength) penetrates deeper layers, which illustrates that the phase velocity of the Rayleigh wave reflects the properties of each layer of pavement (Fig. 3) (Jones 1962). The phenomenon through which the Rayleigh wave velocity varies with wavelength (frequency) is called dispersion, and the plot of velocity versus wavelength (frequency) is called the dispersion curve.

The wavelength can be calculated from the phase velocities of the material as presented in Eq. (1)

$$\lambda = V_{PH}/f \tag{1}$$

where f = frequency (Hz); and V_{PH} = phase velocity (m/s).

By means of the dynamic signal analyzer (Olson Instruments NDE-360 Platform), the time domain records [$X(t)$ and $Y(t)$] are transformed into the frequency domain signals [$X(f)$ and $Y(f)$], and the cross-power spectrum and coherence function are calculated. The dispersion curve is produced from the phase information of the cross-power spectrum, which provides the phase difference of each frequency between two receivers in the SASW test. Therefore, the travel time between the two receivers for each frequency could be determined by Eqs. (2) and (3)

$$\phi(f) = \tan^{-1}\left[\frac{\mathrm{Im}(G_{XY})}{\mathrm{Re}(G_{XY})}\right] \tag{2}$$

$$t(f) = \phi(f)/(360f) \tag{3}$$

where $t(f)$ = time of travel at a certain frequency; $\phi(f)$ = phase difference of a certain frequency; and G_{XY} = cross-power spectrum.

Because the distance between the two receivers is a constant, the Rayleigh wave velocity and the corresponding wavelength can be obtained by Eqs. (4) and (5)

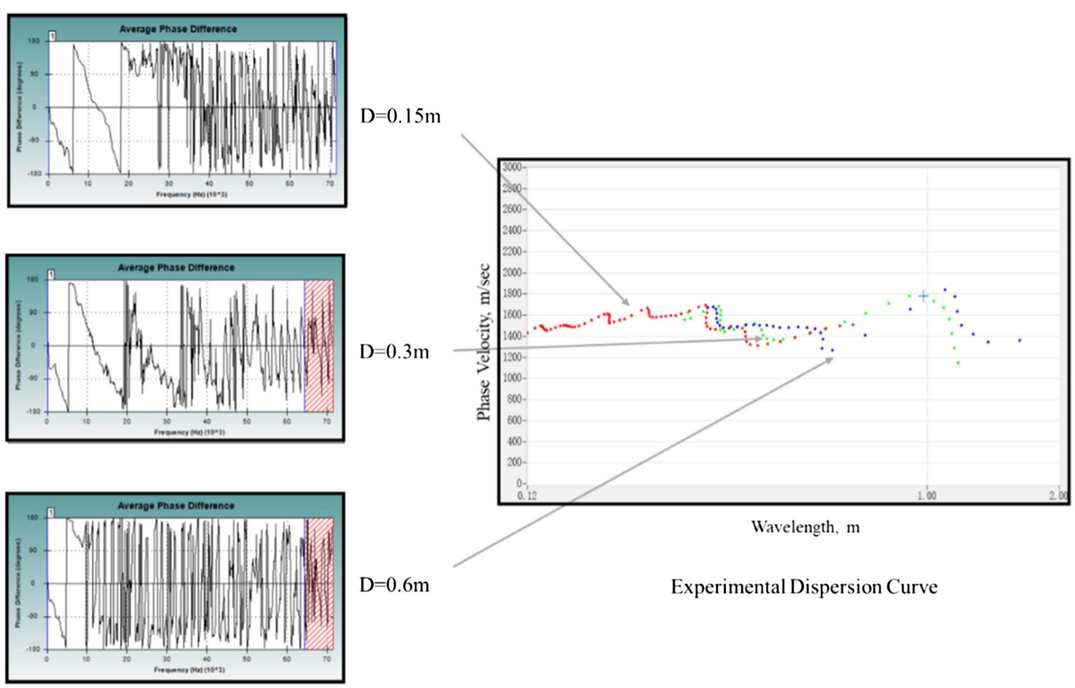

Fig. 3. Typical records for SASW testing.

$$V_R(f) = D/t(f) \quad (4)$$

$$L_R(f) = V_R(f)/f \quad (5)$$

Repeating the steps of Eqs. (2)–(5), the Rayleigh wave velocity corresponding to each wavelength is calculated and the dispersion curve is determined. Combining all the experimental dispersion curves for a series of receiver spacings together, the composite experimental dispersion curves can be constructed.

SASW Data Analysis Procedure

The data output by dynamic signal analyzer are only initial values after Fast Fourier Transform. Further data analysis consists of three steps: (1) interactive masking, (2) determination of composite and representative average dispersion curve, and (3) inversion analysis.

The purpose of the interactive masking is to mask out the unexpected regions that have low-quality phase spectrum and violate the criterion of receiver geometry (Joh 1997). When the composite experimental dispersion curve is determined, as mentioned in the section on spectral analysis of surface wave, a representative average dispersion curve containing 30–50 frequency points will be constructed after some averaging procedures, as proposed by Joh (1997) and Nazarian and Stokoe (1993). The shear wave velocity profile (the plot of shear wave velocity versus depth) can be obtained from the inversion analysis of the average experimental dispersion curve. Actually, the inversion analysis is an automated forward modeling from a reasonable initial guess of the stiffness profile to the final solution. Based on the transfer matrix method and dynamic stiffness matrix method, some theoretical dispersion curves superposing high mode surface waves and body waves are calculated and then compared with the experimental dispersion curve (Kausel and Röesset 1981). If the theoretical and experimental dispersion curves match properly with each other and have the minimum RMS error between them, then an optimum theoretical dispersion curve will be obtained.

The modulus of each pavement layer can be calculated from the following equations based on shear velocity

$$G = \rho \cdot V_s^2 \quad (6)$$

$$\rho = \gamma_t / g \quad (7)$$

$$E = 2G(1 + \mu) \quad (8)$$

where ρ = density of pavement material; γ_t = total unit weight of the pavement; g = gravitational acceleration; G = shear modulus; and E = elastic modulus. Generally, the value of mass density of asphalt is recommended as 2,320 kg/m^3, and the Poisson's ratio is recommended as 0.333 in the initial guess of the stiffness profile.

Attenuation of Modulus in Asphalt Pavement under APT Loading

Experimental Layout

The APT test was conducted to evaluate the modulus attenuation characteristics in asphalt pavement. In this study, the pavement structure was a semirigid base pavement, which consisted of a 300-mm-thick dense graded hot mix asphalt (HMA) mixture above a 300-mm-thick cement stabilized crushed stone layer and subgrade soil, as shown in Fig. 4. The nominal maximum size of the HMA mixture was 13 mm, denoted as AC-13 mixture in this paper.

The MLS66 APT facility, a large full-scale mobile linear accelerated loading test system for pavement, was used for applying loading. The valid loading length of MLS66 was 6 m, the loading amplitude was 150 kN with double wheels, the contact pressure was 0.80 MPa, and the transverse movement was not considered in the experiment. The APT testing lasted 2 months and the cumulative loading applications were up to 2.65 million. The SASW measurement layout was shown in Fig. 5. Tests were conducted along the wheel path 2 at location A and location B.

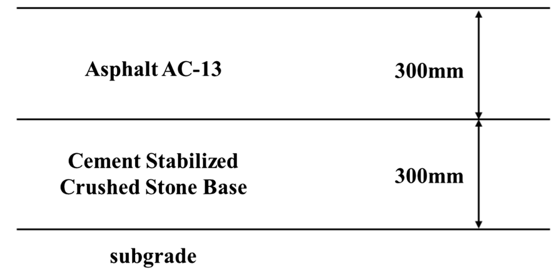

Fig. 4. Pavement structure for APT test.

Measurements were conducted in both the longitudinal direction (along the wheel path) and the transverse direction (perpendicular to the wheel path). In each direction, forward and reversed measurements were performed to determine the surface-wave velocity profile in each SASW testing.

To monitor the change of modulus at different depths, a total of 19 segment layers were used in inversion analysis. The thickness of the 19 segment layers are not evenly divided but increased gradually for better accuracy in the surface layers. Among these segment layers, the asphalt layer was divided into 14 segments, the cement stabilized base was divided into 4 segments, and the soil subgrade was treated as 1 segment.

Analysis and Discussion

Dispersion Curve

During the APT testing, the variation in modulus of asphalt layer was monitored. Fig. 6 presents some typical dispersion curves (the plot of velocity versus wavelength) at different load applications at location A in the longitudinal direction. With the increase of load applications, the velocity value rose firstly and then decreased. The elastic modulus was directly proportional to the shear wave velocity, so the attenuation trend of modulus can be roughly observed. The modulus also rose to a peak value and then decreased. Additionally, when the load applications reached 2 million, the dispersion curve became more difficult to capture in the field, indicating the modulus of the pavement layer had declined to a much lower value.

Because the properties of asphalt were very sensitive to temperature and frequency, it was extremely important to normalize the temperature and frequency to the same value for comparisons of long-term trends in modulus. In this study, the modulus of asphalt layer was corrected to a reference temperature of 21°C and frequency of 30 Hz using the relationship suggested by researchers (Aouad et al. 1993b; Sousa and Monismith 1987), as shown in Eq. (9)

$$E/E_{21^\circ C} = 1.510 - 0.00729T \quad (9)$$

where E = modulus at any temperature; $E_{21^\circ C}$ = modulus at 21°C; and T = temperature in °F. The application range of this equation is the temperature ranging from 0°C (32°F) to 57.8°C (136°F). All the modulus mentioned below had been corrected by temperature and frequency.

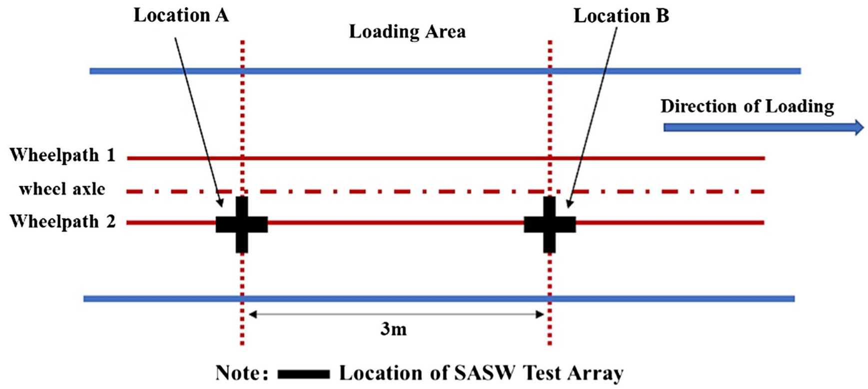

Fig. 5. Location of the SASW test arrays at MLS66 test pad.

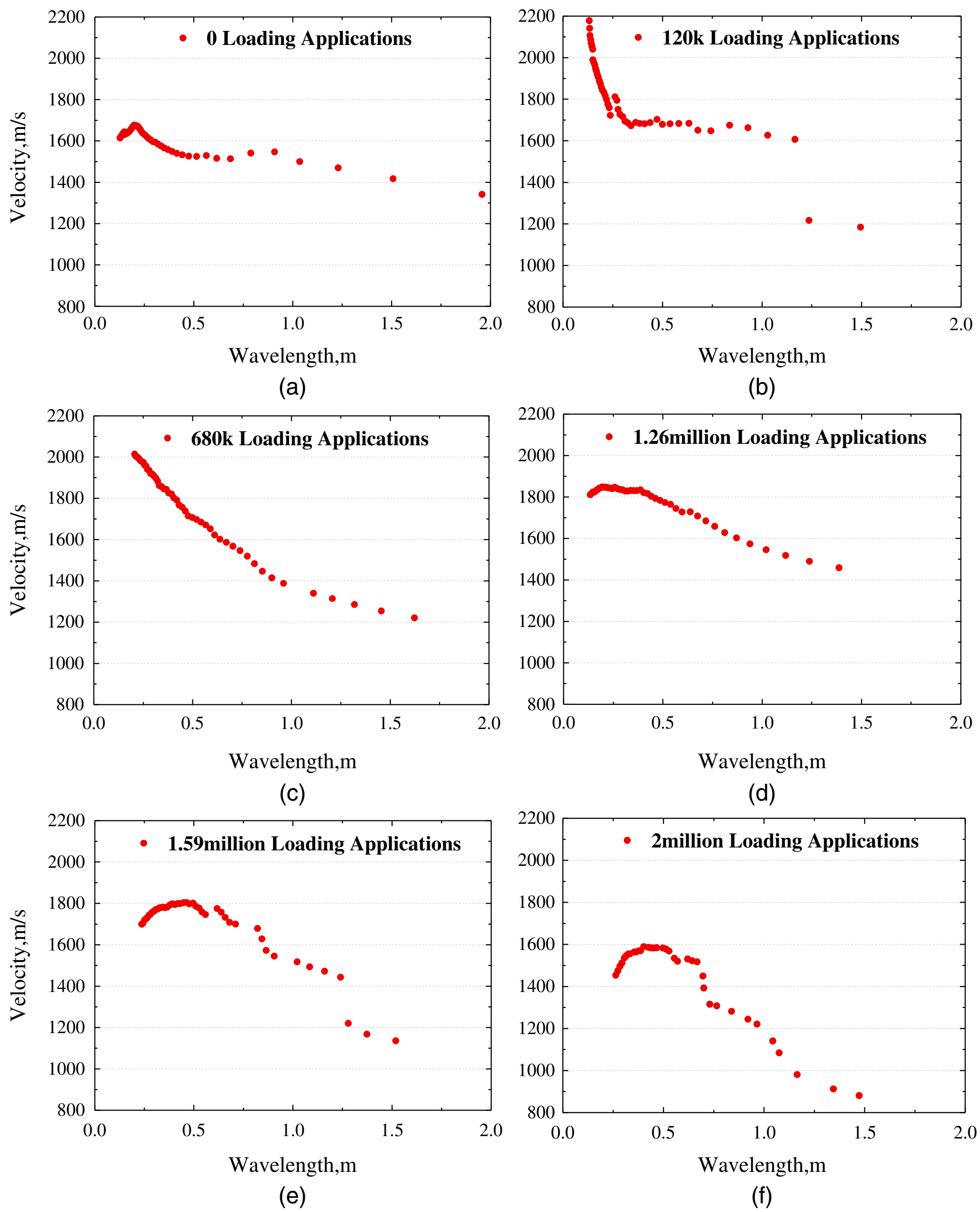

Fig. 6. Dispersion curves obtained from the SASW tests at location A after different loading applications: (a) dispersion curves at 0 loading applications; (b) dispersion curves at 120 k loading applications; (c) dispersion curves at 680 k loading applications; (d) dispersion curves at 1.26 million loading applications; (e) dispersion curves at 1.59 million loading applications; and (f) dispersion curves at 2 million loading applications.

Furthermore, in data analysis and discussion, the 300-mm asphalt layer was divided into three layers: a 100-mm upper layer, 100-mm middle layer, and 100-mm bottom layer to analyze the attenuation characteristics of asphalt mixture over depth. Within each 100-mm layer, the average modulus was calculated from the values of the corresponding segment layers for comparison purpose.

Anisotropic Behavior of Layered Modulus

The in situ modulus of the asphalt mixture was directional dependent due to the anisotropic nature of the asphalt mixture, which could have a prominent influence on the performance of asphalt pavement. It was found that the stiffness of a cored field sample had significant differences in the vertical and horizontal direction, which led to larger shear stress and tensile stress in the asphalt pavement (Wang et al. 2005). In addition, the difference between longitudinal and transverse strains were also obvious under vehicle load, owing to the anisotropic nature of asphalt material (Seo and Lee 2006). Therefore, it is important to study the anisotropic behavior of the layered modulus.

Fig. 7 shows some trends in the elastic modulus as the number of load applications at locations A and B increases. It is found that

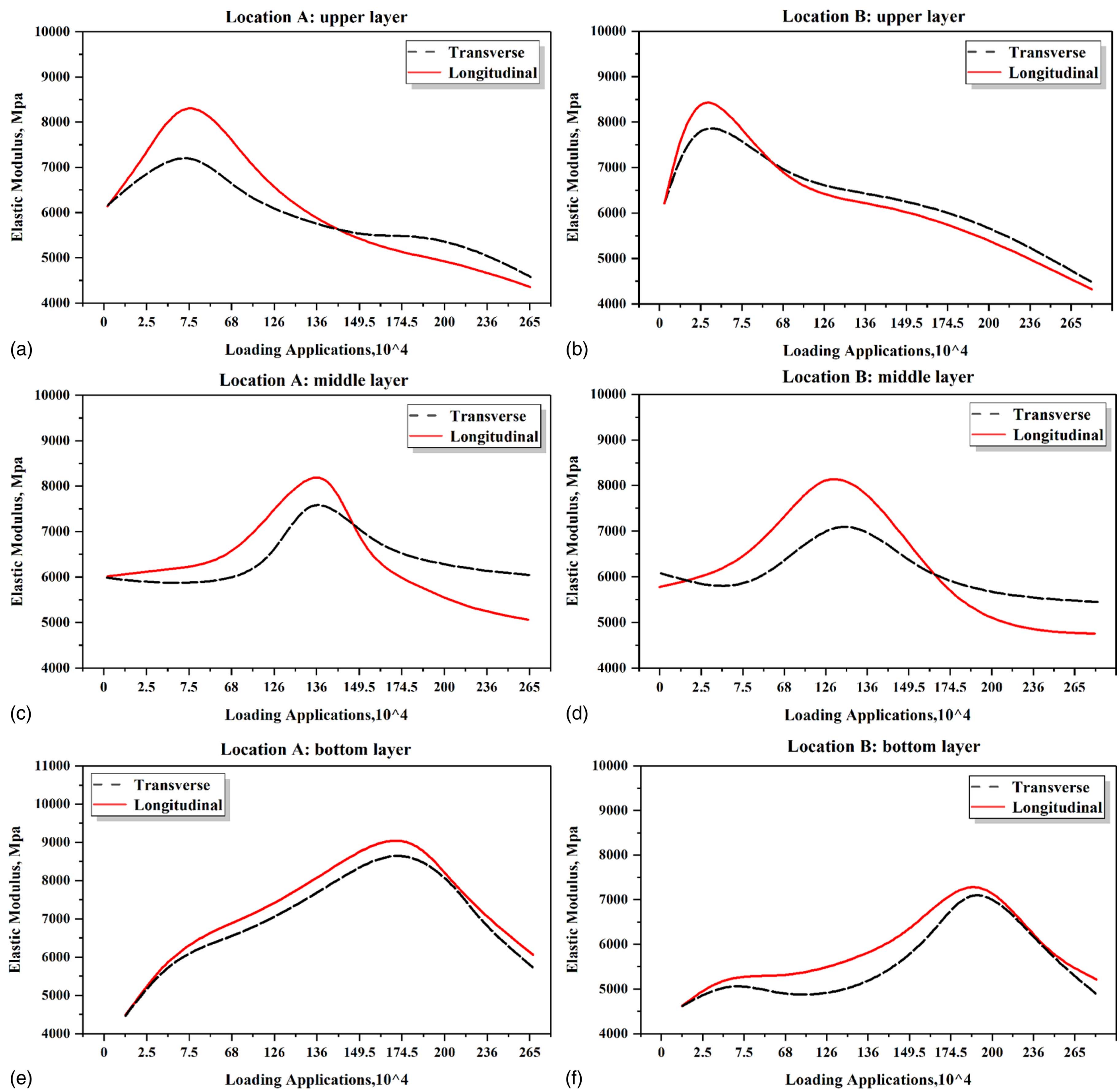

Fig. 7. Variation tendency of corrected elastic modulus of three asphalt layers at two locations: (a) elastic modulus trend of upper asphalt layer at location A; (b) elastic modulus trend of upper asphalt layer at location B; (c) elastic modulus trend of middle asphalt layer at location A; (d) elastic modulus trend of middle asphalt layer at location B; (e) elastic modulus trend of bottom asphalt layer at location A; and (f) elastic modulus trend of bottom asphalt layer at location B.

J. Transp. Eng., Part B: Pavements, 2020, 146(3): 04020039

Table 1. Modulus attenuation of the asphalt layer through entire APT loading (up to 2.65 million)

Location	Direction	The peak value (MPa)	The end value (MPa)	Modulus reduction rate (%)
Location A	Transverse	7,067	5,017	29
	Longitudinal	7,840	4,972	36.7
Location B	Transverse	6,936	4,972	28.3
	Longitudinal	6,978	4,761	31.8

the longitudinal modulus has a greater maximum value, a smaller minimum value, and a higher modulus reduction rate than that of transverse modulus in the upper and middle layers. Table 1 further compares the average modulus of the asphalt layer in both the transverse and longitudinal directions in terms of the peak value (i.e., the highest modulus value during the entire service life) and the end value (i.e., the modulus at 2.65 million load applications, which is also usually the lowest value) during the entire APT loading. As seen, the modulus reduction rate is higher in the longitudinal direction than that in the transverse direction, for both locations A and B. The modulus in the longitudinal direction is more sensitive to change, which could possibly be attributed to the directional compaction and trafficking effect. Overall, the modulus measured in the longitudinal direction was found to be a better indicator to the potential deterioration of the asphalt pavement.

Modulus Attenuation Characteristics along the Depth of Asphalt Layers

The change of the in situ modulus in different asphalt layers could be related to their different performance in the field. Fig. 8 shows some modulus attenuation trends along the depth of asphalt layer (arbitrarily divided into three layers) at locations A and B as the number of load application increases. As seen, at the upper, middle, and bottom layers, the change of modulus follows a similar trend, increasing first to a peak value and then decreasing. However, the upper layer reaches the peak value at an earlier load cycle, then the middle layer reaches the peak value at around 1.3 million loading applications, and finally the bottom layer is peaked at about 1.75–2 million loading applications. With a semirigid base structure, it is reasonable to understand that the upper layer has more deterioration under traffic loading than the bottom layer and cracking is most probably to initiate in the upper layer (Pellinen et al. 2004; Sun et al. 2018).

The surface-opening cracks had been observed to appear at locations A and B during approximately 2.35–2.5 million load applications. In order to explore the general modulus attenuation at the crack occurrence, the modulus measured at both locations A and B were average. From the modulus reduction rate measured at the upper asphalt layer (Table 2), it was obvious that the modulus reduction rate reached around 40% measured in the transverse direction and 50% measured longitudinally when cracks appeared.

General Trend of Modulus Attenuation in Asphalt Layer

Determining the general trend of modulus attenuation in the entire asphalt layer is significant for understanding the pavement

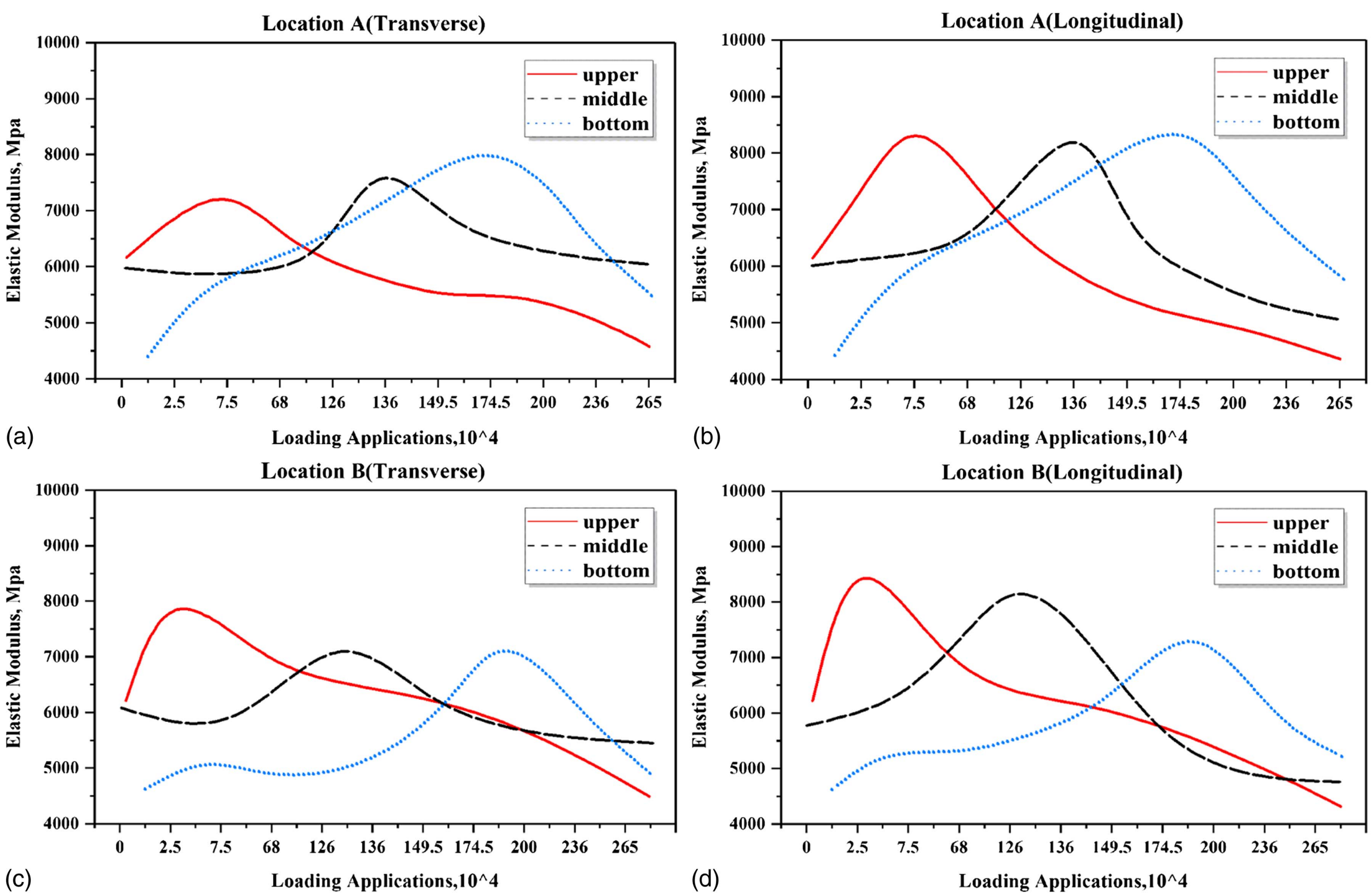

Fig. 8. Variation tendency of elastic modulus at different directions at two locations: (a) the transversely modulus trend at location A; (b) the longitudinally modulus trend at location A; (c) the transversely modulus trend at location B; and (d) the longitudinally modulus trend at location B.

Table 2. Modulus attenuation of the three asphalt layers

Direction	Asphalt layer	The peak value (MPa)	The value at crack generation (MPa)	Modulus reduction rate (%)
Transverse	Upper layer	7,660	4,638	39.5
	Middle layer	7,654	6,583	14
	Bottom layer	8,253	5,837	29.3
Longitudinal	Upper layer	8,368	4,282	48.8
	Middle layer	8,253	5,246	36.4
	Bottom layer	8,390	6,009	28.4

deterioration and estimating the remaining life of the pavement. Fig. 9 shows the trend of modulus change versus number of loading cycles combining modulus from all layers and both directions. Based on the results from two locations, it is suggested that the change of modulus under traffic loading can generally be divided into four stages: (1) stage I, the modulus increases with trafficking, which could be a result of the secondary consolidation/compaction effect (Walubita et al. 2000); (2) stage II, the modulus decreases slowly and slightly; (3) stage III, the modulus remains relatively stable; and (4) stage IV, the modulus begins to reduce dramatically. It is worth noting that such a trend was developed based on the APT test without considering traffic wandering and aging effect. Further evaluation based on actual field testing would be greatly beneficial; however, it would be extremely costly and time consuming to develop a complete modulus attenuation curve based on actual field traffic.

Characteristics of Modulus in In-Service Pavement

Experimental Layout and Procedure

In this section, the SASW measurement was conducted on an in-service pavement to quantify the relationship between modulus reduction and pavement deterioration as well as cracking. The pavement site was located on the Ningyang Highway in Nanjing, Jiangsu, China. The structure of the pavement is shown in Fig. 10.

Two types of experiment and analysis were performed: (1) obtaining the modulus attenuation trends by comparing the modulus at the wheel-path location (with traffic) and at shoulder (no traffic); and (2) quantifying modulus reduction rate for crack occurrence by comparing the modulus near and away from a crack with the modulus at shoulder. Fig. 11 shows the location of the SASW tests.

Analysis and Discussion

Comparison of Wheel-Path and Shoulder Modulus of In-Service Pavement

Four cross-sections without visible cracks and distresses were selected to conduct the SASW testing at the wheel-path and shoulder locations and to evaluate the pavement deterioration trend under vehicle load. For convenience, the four sections were labeled as A, B, C, and D, respectively.

After inversion analysis and some postprocesses, including temperature and frequency correction, the comparisons of the elastic modulus of asphalt layer measured at the wheel-path and shoulder of four cross-sections were performed. For comparison, the values of modulus in each asphalt layer were averaged respectively. Table 3 summarizes the modulus reduction rate of the four cross-sections for both the transverse direction and longitudinal direction. As shown, the modulus at the wheel path is higher than at the shoulder for locations A and D, indicating pavement is in good condition. At locations B and C, obvious modulus reduction is noticed. The change of modulus is also different in different layers.

Field cores were taken at the wheel paths of four cross-sections where the SASW testing had been conducted, for visual verification of whether the cracks had occurred in the internal of the asphalt layer, especially where the modulus decreased considerably. It was found that there were no visible cracks occurred in the four core samples. Combining the modulus reduction rates shown in Table 3, it was noticed that cracking appeared not visible with modulus reduction level up to 35%.

The indirect tension tests (IDTs) were conducted on the field cores at the wheel paths of sections B and D. Table 4 summarizes the dynamic modulus results at 21°C temperature and 1 Hz frequency. Because the modulus measured from the SASW method was corrected to a reference frequency of 30 Hz, and there existed difference between the dynamic modulus and elastic modulus, the specific modulus value calculated from these two methods were not directly comparable. Fig. 12 presents a correlation of the modulus determined by the SASW method and IDT test, respectively, for the modulus of the upper, middle, and bottom asphalt layers at two sections. With the Pearson correlation coefficient being 0.8 and

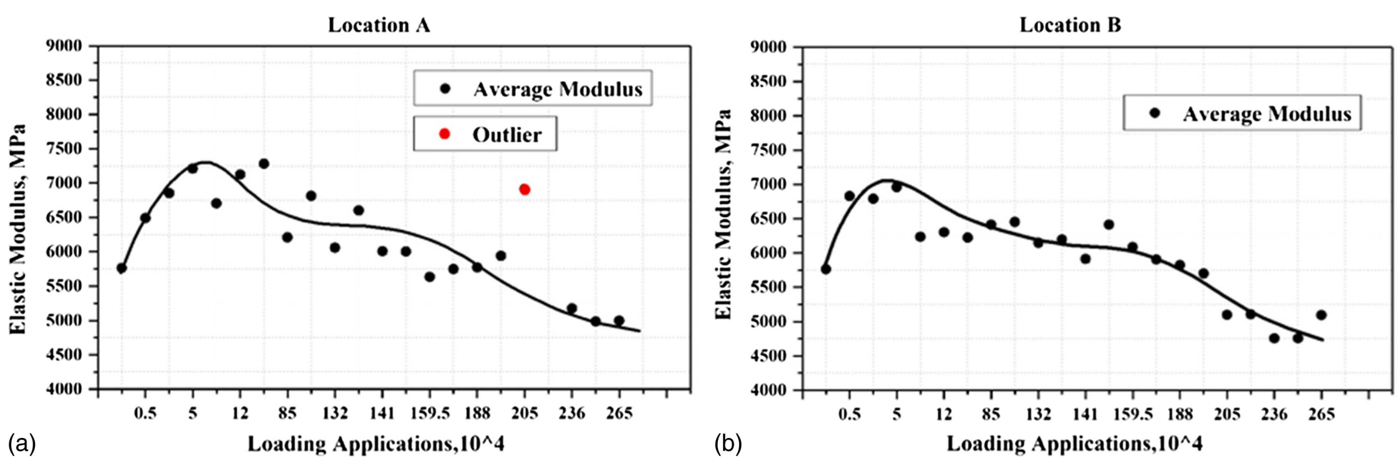

Fig. 9. Variation tendency of elastic modulus for the whole asphalt layers at two locations: (a) the trend in modulus at location A; and (b) the trend in modulus at location A.

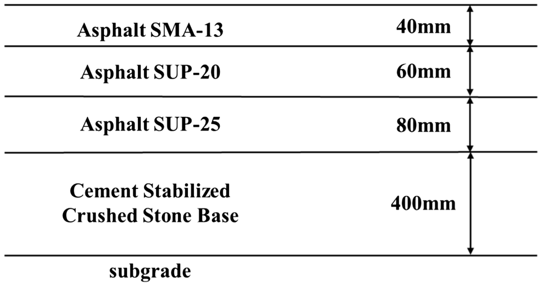

Fig. 10. Pavement structure.

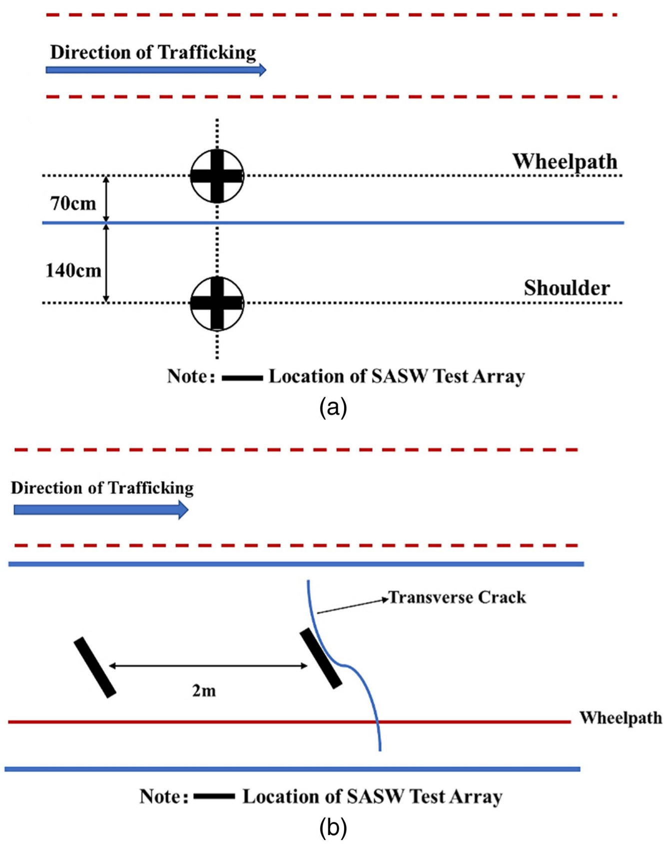

Fig. 11. Location of the SASW tests on in-service pavement: (a) test locations at wheel path and shoulder; and (b) test locations at and away from a transverse cracking.

higher, it is confirmed that there is a good correlation between the modulus obtained from these two methods.

Relationship between Modulus Reduction and Cracking Distress

SASW testing was conducted on three typical transverse cracks (denoted as E, F, and G) to investigate the modulus attenuation at visible cracks and to establish the relationship between cracking distress and modulus attenuation. Transverse cracking was selected because it was more dominant in the selected pavement section. The away-crack location was approximately 2 m away from the cracks, as shown in Fig. 11(b). The SASW testing array can only be placed parallel to the crack because the Rayleigh waves generated by the impact source cannot propagate through air voids.

Table 3. Modulus reduction rate between wheel paths and shoulders

Location	Direction	Modulus reduction rate [a](%) SMA-13 upper layer	SUP-20 middle layer	SUP-25 bottom layer
Section A	Transverse	[b]	[b]	[b]
	Longitudinal	23.5	[b]	[b]
Section B	Transverse	30.6	12.3	15.8
	Longitudinal	26.7	34	8.2
Section C	Transverse	30.1	[b]	12.7
	Longitudinal	24.6	[b]	34.9
Section D	Transverse	[b]	[b]	[b]
	Longitudinal	[b]	[b]	[b]

[a]The modulus reduction rate is calculated as $(1-E_{\text{wheel-path}}/E_{\text{shoulder}})$.
[b]The modulus at the wheel path is larger than that at the shoulder, and the reduction rate is negative.

Table 4. Modulus comparison between IDT tests and SASW tests

Location	Asphalt layer	IDT at 20°C and 1 Hz/MPa	SASW at 21°C and 30 Hz/MPa Average	Transverse	Longitudinal
Section B	Upper layer	2,507	3,167	3,079	3,256
	Middle layer	2,632	3,958	4,524	3,392
	Bottom layer	3,413	4,282	4,098	4,467
Section D	Upper layer	2,566	4,101	3,555	4,646
	Middle layer	2,703	4,523	4,155	4,890
	Bottom layer	3,020	5,790	5,803	5,778

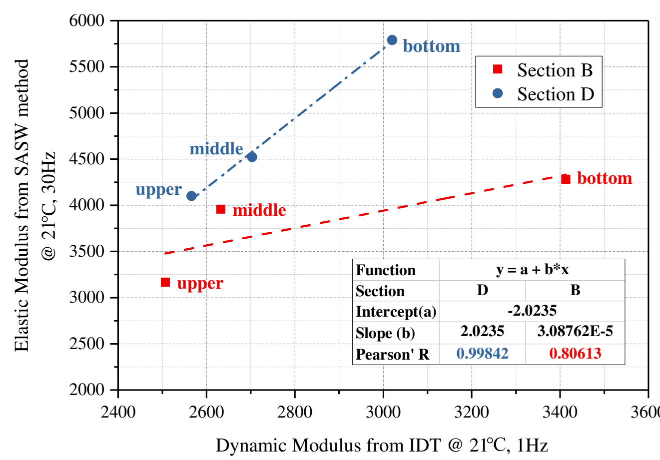

Fig. 12. Correlation of elastic modulus of asphalt layer by the SASW method and IDT.

Fig. 13 shows the plots of modulus variation along the depth between the near-crack location and away-crack location after bearing the same vehicle loads. It is apparent that in the asphalt layers the modulus measured at away-crack locations are much larger than the modulus near the cracks, while their base modulus matches each other quite well. In other words, crack appearance is always accompanied by modulus reduction.

In addition, Table 5 summarizes the modulus and its reduction rate results for at-crack and near-crack locations, using the shoulder

J. Transp. Eng., Part B: Pavements, 2020, 146(3): 04020039

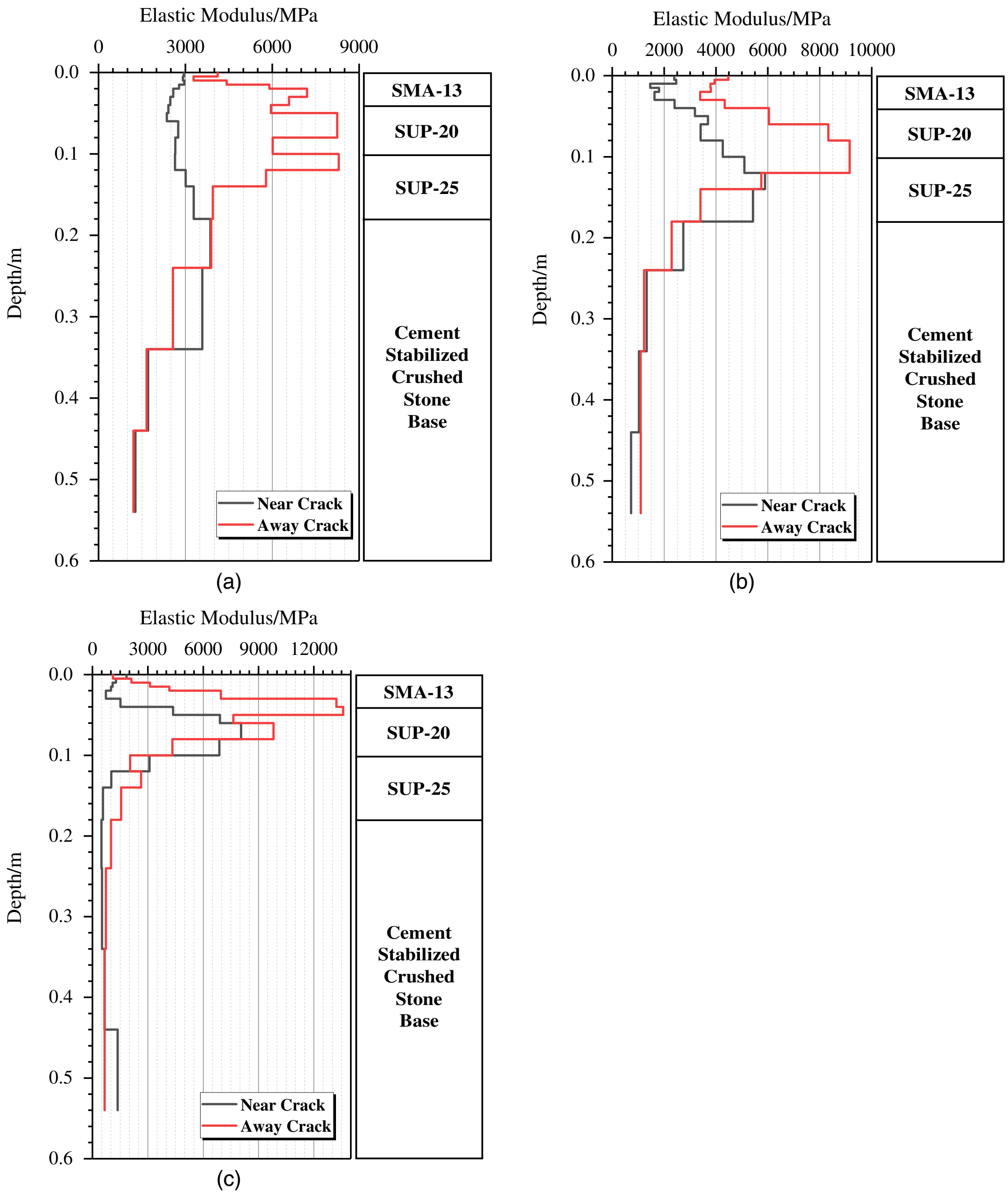

Fig. 13. Comparison of modulus measured at three transverse cracks between near-crack location and away-crack location: (a) modulus measured at crack E; (b) modulus measured at crack F; and (c) modulus measured at crack G.

Table 5. Modulus reduction at three transverse cracks

Asphalt layer	Location	Crack E Value (MPa)	Crack E Reduction rate (%)	Crack F Value (MPa)	Crack F Reduction rate (%)	Crack G Value (MPa)	Crack G Reduction rate (%)
SMA-13 upper layer	Shoulder	5,521.8	0	4,300	0	5,328.2	0
	Near-crack	2,777.6	49.7	2,025.9	52.9	1,242.7	76.7
	Away-crack	5,251.8	4.9	3,955.2	8.02	5,112.6	4.0
SUP-20 middle layer	Shoulder	5,849.1	0	7,385.4	0	6,559.2	0
	Near-crack	2,543.0	56.5	3,635.4	50.8	6,549.7	0.14
	Away-crack	7,115.4	[a]	7,388.1	[a]	8,840.9	[a]
SUP-25 bottom layer	Shoulder	4,645.7	0	2,555	0	3,645.7	0
	Near-crack	2,978.6	35.9	5,469.6	[a]	1,556.4	57.3
	Away-crack	6,012.8	[a]	6,101.1	[a]	2,072.6	43.2

[a]The modulus is larger than that at the shoulder, and the reduction rate is negative.

modulus as a reference because at shoulder the pavement experienced minimum traffic loading and can have minimum damage. Based on this table, the following observations can be made:

- When cracking occurs in the pavement, it is normally accompanied by clear modulus reduction. At all crack locations (cracks E, F, and G), the surface SMA-13 layer receives high modulus reduction (50% or higher) compared to the no-crack location, suggesting that the crack appearance can be associated with a modulus reduction of 50% or higher.
- Based on the measured modulus reduction rate in each layer, it is possible that cracks E and F could extend through the upper and middle asphalt layers, while the crack G may only occur in the upper and bottom asphalt layers but not in the middle layer. It is possible that the SASW method can be used as an effective tool for identifying internal crack location. Unfortunately, due to practical reasons, the field cores at the crack location were not available and these assumptions cannot be verified at this moment.

Summary and Conclusions

This paper presented two case studies to demonstrate the capability of using the SASW method to monitor the long-term variations and attenuation of modulus in asphalt pavement under the traffic loading and propose the relationship between the modulus and pavement cracking distress. Although based on limited data due to the high cost and difficulty of field experiment, the following findings demonstrated that the SASW method can be an effective method to study the pavement performance deterioration. More experiments in the field are recommended in future research to verify the results:

- The pavement deterioration characteristics can be quantified using the modulus concept. The long-term trend of in situ modulus of asphalt pavement under vehicle loading can be divided into four stages: (1) stage I, the modulus increases with trafficking, which could result from secondary consolidation/compaction effect; (2) stage II, the modulus decreases slowly and slightly; (3) stage III, the modulus remained relatively stable; and (4) stage IV, the modulus begins to reduce dramatically. In addition, the attenuation tendency of the in situ modulus of asphalt mixture was different along the depth.
- The change of modulus follows different trends in different layers of the pavement as a joint effect of pavement structure and the traffic loading. The SASW method has the capability of identifying such modulus change profile along the pavement depth.
- Evaluated by the modulus, asphalt concrete was anisotropic in horizontal plane. The longitudinal modulus was more sensitive to the modulus variation than the transverse modulus under the vehicle load presented by its faster reduction rate. Hence, the modulus measured in the longitudinal direction could be more reasonable for evaluating the deterioration of pavement performance.
- The high reduction rate of the modulus can be an indication of the onset of the microcrack in pavement layers. The occurrence of crack at the asphalt layer was associated with a modulus reduction rate of approximately 40%–50%. This finding was consistent with the laboratory fatigue criterion of 50% initial modulus reduction and provided supportive information for fatigue criteria determination.
- The SASW method might be used to identify the location of the internal crack initiation and how many layers it has penetrated through.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author upon reasonable request. Specifically, they include: SASW measurement data; IDT testing data.

Acknowledgments

The research team would like to acknowledge the financial support from the Jiangsu Highway Engineering Maintenance Co., Ltd and the National Key R&D Program of China (Grant No. 2018YFB1600100). The contents of this paper only reflect the views of the authors and do not reflect the official views or policies of the sponsors.

References

Alexander, D. R., S. D. Kohn, and W. P. Grogan. 1989. “Nondestructive testing techniques and evaluation procedures for airfield pavements.” In *Nondestructive testing of pavements and backcalculation of Moduli*. West Conshohocken, PA: ASTM.

Aouad, M. F., I. I. Stokoe, H. Kenneth, and R. C. Briggs. 1993a. “Stiffness of asphalt concrete surface layer from stress wave measurements.” *Transp. Res. Rec.* 1384 (1): 29–35.

Aouad, M. F., K. H. Stokoe, and J. M. Roesset. 1993b. *Evaluation of flexible pavements and subgrades using the spectral-analysis-of-surface-waves (SASW) method*. Washington, DC: Federal Highway Administration, USDOT.

ASTM. 2003. *Standard test method for deflections with a falling-weight-type impulse load device*. West Conshohocken, PA: ASTM.

Ellis, T. 2008. “A Comparison of nondestructive testing backcalculation techniques for rigid and flexible pavements.” Civil Engineering Undergraduate Honors Theses. Dept. of Civil Engineering, Univ. of Arkansas, Fayetteville.

Hasaninia, M., and F. Haddadi. 2018. “Studying engineering characteristics of asphalt binder and mixture modified by nanosilica and estimating their correlations.” In *Advances in materials science and engineering*. London: Hindawi.

Hazra, S., and J. Kumar. 2014. “SASW testing of asphaltic pavement by dropping steel balls.” *Int. J. Geotech. Eng.* 8 (1): 34–45. https://doi.org/10.1179/1938636213Z.00000000051.

Heisey, J. S., K. H. Stokoe, W. R. Hudson, and A. H. Meyer. 1982. *Determination of in situ shear wave velocities from spectral analysis of surface waves*. Publication FHWA/TX-82/34+256-2. Washington, DC: Federal Highway Administration, USDOT.

Hintz, C., and H. Bahia. 2013. “Simplification of linear amplitude sweep test and specification parameter.” *Transp. Res. Rec.* 2370 (1): 10–16. https://doi.org/10.3141/2370-02.

Ismail, M. A., A. R. Samsudin, A. G. Rafek, and K. A. M. Nayan. 2012. “Road pavement stiffness determination using SASW method.” *J. Civ. Eng. Sci. Technol.* 3: 9–16. https://doi.org/10.33736/jcest.97.2012.

Joh, S., and K. H. Stokoe. 1997. *Advances in interpretation and analysis techniques for spectral (SASW) measurements by offshore*. New York: National Science Foundation.

Jones, R. 1962. “Surface wave technique for measuring the elastic properties and thickness of roads: Theoretical development.” *Br. J. Appl. Phys.* 13 (1): 21–29. https://doi.org/10.1088/0508-3443/13/1/306.

Kausel, E., and J. M. Röesset. 1981. “Stiffness matrices for layered soils.” *Bull. Seismol. Soc. Am.* 71 (6): 1743–1761.

Kumar, J., and T. Naskar. 2015. “Effects of site stiffness and source to receiver distance on surface wave tests’ results.” *Soil Dyn. Earthquake Eng.* 77 (Oct): 71–82. https://doi.org/10.1016/j.soildyn.2015.04.022.

Lee, H.-J., J. S. Daniel, and Y. R. Kim. 2000. “Continuum damage mechanics-based fatigue model of asphalt concrete.” *J. Mater. Civ. Eng.* 12 (2): 105–112. https://doi.org/10.1061/(ASCE)0899-1561(2000)12:2(105).

Lee, N. K., F. Hugo, and K. H. Stokoe. 1997. "Detection and monitoring of cracks in asphalt pavement under Texas mobile load simulator testing." *Transp. Res. Rec.* 1570 (1): 10–22. https://doi.org/10.3141/1570-02.

Mobasher, B., M. S. Mamlouk, and H. M. Lin. 1998. "Evaluation of crack propagation properties of asphalt mixtures." *J. Transp. Eng.* 123 (5): 405–413. https://doi.org/10.1061/(ASCE)0733-947X(1997)123:5(405).

Nazarian, S., and K. H. Stokoe. 1983. *Evaluation of moduli and thicknesses of pavement systems by spectral-analysis-of-surface-waves method*. Rep. No. FHWA/TX-83/26+256-4. Austin, TX: Univ. of Texas at Austin.

Nazarian, S., and K. H. Stokoe. 1984. "Nondestructive testing of pavements using surface waves." *Transp. Res. Rec.* 993 (1): 67–79.

Nazarian, S., and K. H. Stokoe. 1985. *In situ determination of elastic moduli of pavement systems by spectral-analysis-of-surface-waves method: Practical aspects*. Rep. No. FHWA/TX-86/l3+368-lF. Washington, DC: Federal Highway Administration, USDOT.

Nazarian, S., and K. H. Stokoe. 1986. *In situ determination of elastic moduli of pavement systems by spectral analysis of surfaces waves method (theoretical aspects)*. Rep. No. FHWA/TX-87/46+437-2. Washington, DC: Federal Highway Administration.

Nazarian, S., and K. H. Stokoe. 1993. "Automated surface wave method: Field testing." *J. Geotech. Eng.* 119 (7): 1094–1111. https://doi.org/10.1061/(ASCE)0733-9410(1993)119:7(1094).

Pellinen, T., G. Rowe, and K. Biswas. 2004. *Evaluation of surface (top down) longitudinal wheel path cracking*. Rep. No. FHWA/IN/JTRP-2004/6. West Lafayette, IN: Joint Transportation Research Program.

Popovics, J. S., and O. Abraham. 2010. *Surface wave techniques for evaluation of concrete structures: Non-destructive evaluation of reinforced concrete structures: Non-destructive testing methods.* Cambridge, UK: Woodhead Publishing.

Rosyidi, S. 2004. "Measurement of subgrade stiffness using the SASW method." In *Proc., Malaysian Geotechnical Conf.*, 2–7. New York: Ministry of Science, Technology and Environmental.

Ryden, N. 2009. "Surface wave testing of pavements." *J. Acoust. Soc. Am.* 125 (4): 2603. https://doi.org/10.1121/1.4783908.

Seo, Y. G., and K.-H. Lee. 2006. "Behavior of asphalt pavement subjected to a moving vehicle. I: The effect of vehicle speed, axle-weight, and tire inflation pressure." *J. Korean Soc. Civ. Engineers* 26 (5D): 831–838.

Shen, S., and X. Lu. 2010. "Energy based laboratory fatigue failure criteria for asphalt materials." *J. Test. Eval.* 39 (3): 313–320. https://doi.org/10.1520/JTE103088.

Sousa, J. B., and C. L. Monismith. 1987. "Dynamic response of paving materials." *Transp. Res. Rec.* 1136 (1): 57–68. https://doi.org/10.1520/JTE103088.

Stokoe, K. H., S.-H. Joh, and R. D. Woods. 2004. "Some contributions of in situ geophysical measurements to solving geotechnical engineering problems." In *Proc., ISC-2 on Geotechnical and Geophysical Site Characterization*, edited by A. Viana da Fonseca and P. W. Mayne, 97–132. Porto, Portugal: School of Civil, Environmental and Mining Engineering.

Stokoe, K. H., and S. Nazarian. 1985. "Use of Rayleigh waves in liquefaction studies." In *Proc., Measurement and Use of Shear Wave Velocity for Evaluating DynamicSoil Properties*, 1–17. Reston, VA: ASCE.

Storme, M., J. M. Konrad, and R. Fortier. 2004. "Assessment of thaw weakening in pavement stiffness using the spectral analysis of surface waves." *Can. Geotech. J.* 41 (3): 510–522. https://doi.org/10.1139/t03-095.

Sun, L., G. Wang, H. Zhang, and L. Liu. 2018. "Initiation and propagation of top-down cracking in asphalt pavement." *Appl. Sci.* 8 (5): 774. https://doi.org/10.3390/app8050774.

Svasdisant, T., M. Schorsch, G. Y. Baladi, and S. Pinyosunun. 2002. "Mechanistic analysis of top-down cracks in asphalt pavements." *Transp. Res. Rec.* 1809 (1): 126–136. https://doi.org/10.3141/1809-15.

Tarefder, R. A., and M. U. Ahmed. 2013. "Consistency and accuracy of selected FWD backcalculation software for computing layer modulus of airport pavements." *Int. J. Geotech. Eng.* 7 (1): 21–35. https://doi.org/10.1179/1938636212Z.0000000009.

Terrell, R. G., B. R. Cox, K. H. S. Ii, J. J. Allen, and D. Lewis. 2003. "Field evaluation of the stiffness of unbound aggregate base layers in inverted flexible pavements." *Transp. Res. Rec.* 1837 (1): 50–60. https://doi.org/10.3141/1837-06.

Timm, D. H., and A. L. Priest. 2008. "Flexible pavement fatigue cracking and measured strain response at the NCAT test track." In *Presented at 87th Annual Meeting of the Transportation Research Board*. Washington, DC: Transportation Research Board.

Walubita, L. F., F. Hugo, and A. Epps. 2000. *Performance of rehabilitated lightweight aggregate asphalt concrete pavements under wet and heated model mobile load simulator trafficking: A comparative study with the TxMLS*. Austin, TX: Univ. of Texas at Austin.

Wang, L., L. R. Hoyos, J. Wang, G. Voyiadjis, and C. Abadie. 2005. "Anisotropic properties of asphalt concrete: Characterization and implications for pavement design and analysis." *J. Mater. Civ. Eng.* 17 (5): 535–543. https://doi.org/10.1061/(ASCE)0899-1561(2005)17:5(535).

Widodo, W. 2009. "Experimental investigation of seismic parameters and bearing capacity of pavement subgrade using surface wave method." *Semesta Teknika* 12 (1): 68–77.

Yang, M. 2007. *Study on dynamic modulus of asphalt mixture.* [In Chinese.] Doctoral dissertation. Changsha Univ. of Science and Technology.

Zhao, K. 2015. *Dynamic modulus back-calculation and bearing capacity evaluation for asphalt pavement structure.* [In Chinese.] Xi'an, China: Chang'an Univ.

Zofka, A., M. Maliszewski, and D. Maliszewska. 2017. "Glass and carbon geogrid reinforcement of asphalt mixtures." Supplement, *Road Mater. Pavement Des.* 18 (S1): 471–490. https://doi.org/10.1080/14680629.2016.1266775.