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RESEARCH ARTICLE

# Bridging the gap between laboratory and field moduli of asphalt layer for pavement design and assessment: A comprehensive loading frequency-based approach

**Huailei CHENG[a,b], Liping LIU[a], Lijun SUN[a*]**

[a] *The Key Laboratory of Road and Traffic Engineering (Ministry of Education), Tongji University, Shanghai 201804, China*
[b] *Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong 999077, China*
[*] *Corresponding author. E-mail: ljsun@tongji.edu.cn*



**ABSTRACT** Asphalt pavement is a key component of highway infrastructures in China and worldwide. In asphalt pavement design and condition assessment, the modulus of the asphalt mixture layer is a crucial parameter. However, this parameter varies between the laboratory and field loading modes (i.e., loading frequency, compressive or tensile loading pattern), due to the viscoelastic property and composite structure of the asphalt mixture. The present study proposes a comprehensive frequency-based approach to correlate the asphalt layer moduli obtained under two field and three laboratory loading modes. The field modes are vehicular and falling weight deflectometer (FWD) loading modes, and the laboratory ones are uniaxial compressive (UC), indirect tensile (IDT), and four-point bending (4PB) loading modes. The loading frequency is used as an intermediary parameter for correlating the asphalt layer moduli under different loading modes. The observations made at two field large-scale experimental pavements facilitate the correlation analysis. It is found that the moduli obtained via laboratory 4PB tests are pretty close to those of vehicular loading schemes, in contrast to those derived in UC, IDT, and FWD modes, which need to be adjusted. The corresponding adjustment factors are experimentally assessed. The applications of those adjustment factors are expected to ensure that the moduli measured under different loading modes are appropriately used in asphalt mixture pavement design and assessment.

**KEYWORDS** asphalt mixture layer, stiffness modulus, loading mode, UC/4PB/IDT, FWD, frequency

## 1 Introduction

Asphalt pavement constitutes one of the major pavement structures for highways or steel bridge roadways in China and worldwide, thanks to its superior riding quality, low running noise, and easy maintenance. In the design or condition assessment procedures of asphalt pavements, the stiffness modulus of the asphalt mixture layer is a crucial input parameter [1–4]. The asphalt mixture is one type of composite containing asphalt binder, aggregate and air void. Consequently, the mixture's stiffness modulus is dependent on the individual properties of those components, as well as the interactions of different components. For asphalt binder, it is viscous with the stiffness changing with temperature and loading frequency [5–7]. The aggregate interlock effect within the mixture, however, is influenced by the loading mode, with the interlock effect being much more predominant under compressive mode than under tensile mode [8,9]. Like cement, the asphalt mixture under compressive stress is stiffer than when under tensile stress [10–16]. As a result, the asphalt mixture's modulus depends on the temperature, loading frequency and stress state (compressive or tensile). Those influence factors can also be coupled, making the asphalt mixture modulus much more complicated to be determined.

In pavement design, several commonly used design approaches, such as the US mechanistic-empirical pavement design guide (MEPDG) and the China design method [3,17,18], adopt the laboratory uniaxial

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compressive (UC) dynamic modulus test to determine the asphalt mixture's modulus. In the UC test, the influences of loading frequency and temperature on the modulus of asphalt layer are taken into account, while the stress state effect is ignored. The UC test employs a one-dimensional compressive loading, and hence it assesses only the compressive modulus of the asphalt mixture at the material level. However, the asphalt mixture within the field pavement structure is subjected to compressive and tensile stresses [19,20]. Thus its behavior is controlled by both tensile and compressive moduli at the structural level. Therefore, the compressive modulus obtained via the UC mode is insufficient for reflecting the tensile nature of a field asphalt layer. Apart from the UC loading mode, two other laboratory loading modes, namely four-point bending (4PB) and indirect tensile (IDT) ones, have been used by previous researchers to test the modulus of asphalt mixture [13,21,22]. In 4PB and IDT modes, both compressive and tensile stresses are applied to the asphalt mixture specimens. As a result, those two modes show potentials to better simulate the stress state within a field asphalt layer than the UC loading mode. The above discussions reveal that it is necessary to further assess the appropriateness of using UC dynamic modulus for characterizing the modulus properties of field asphalt layer. Similarly, if the moduli obtained from IDT and 4PB loading modes are of interest, their suitability for simulating field conditions also needs to be evaluated. To assess these objectives of appropriateness, the modulus of asphalt layer induced by laboratory loading mode (UC/IDT/4PB) has to be compared and correlated with that under field vehicular loading mode.

In pavement condition assessment, the asphalt layer modulus is widely evaluated via the falling weight deflectometer (FWD) test. The deflection basin measured in FWD test is used to back-calculate the asphalt layer's modulus [23–28]. The back-calculated modulus is then used to evaluate the asphalt layer conditions or applied as the in-situ modulus for pavement rehabilitation/overlay design [3]. Although FWD provides a convenient tool for assessing the modulus of the existing asphalt layer, one issue remains unclear on the applicability of FWD test results. The FWD loading time is very short (approx. 0.030 s) [29], in contrast to that of vehicular loading [30–34]. As a result, the FWD loading frequency significantly exceeds the vehicular loading one. Due to this discrepancy in loading frequencies, the vehicular loading mode generates a different asphalt layer modulus as compared with the FWD loading mode [35]. For pavement assessment or rehabilitation design, the vehicular-loading-induced modulus is actually required. Hence, the asphalt layer modulus back-calculated from the FWD test may need to be adjusted before its utilization in the assessment or rehabilitation design procedure. To derive the respective adjustment factor, the modulus of the asphalt layer under FWD loading mode is required to be correlated with that under vehicular mode.

In summary, various field loading modes (vehicular loading and FWD loading) and laboratory modes (UC/4PB/IDT) tend to produce different modulus values for asphalt mixture, due to the discrepancies in stress states and loading frequencies. The correlations between asphalt layer moduli under those loading modes are required, to facilitate choice of appropriate modulus value in pavement design and assessment. Based on the relevant research results earlier obtained by the authors' research team [17,18,29,36], this study aims to develop a comprehensive approach linking the asphalt layer moduli under various loading modes. First, the asphalt layer moduli under FWD, vehicular, and three laboratory loading modes are determined. The loading frequency is used as an intermediary parameter for correlating asphalt layer modulus under these loading modes. The data collected from two field large-scale pavement test sections are utilized to verify this approach's feasibility. Through the approach, asphalt layer moduli obtained under different loading modes are appropriately correlated and adjusted for estimating the required modulus of the *in-situ* asphalt layer.

## 2 Procedures for determining moduli of asphalt layer under different laboratory and field loading modes

### 2.1 Procedure for determining the modulus of asphalt mixture layer under falling weight deflectometer mode

The deflection basin measured from the FWD test is applied to back-calculate the asphalt layer modulus under FWD mode. However, the back-calculation results can be biased by human error, and depend on the user experience as well as the initially assumed input moduli. To mitigate the above problems, this study adopts an upgraded back-calculation procedure that has been recently developed by the authors' research group [36–38]. The procedure uses the inertial point first to determine the subgrade layer's modulus of the pavement. The inertial point refers to a distinctive offset distance from the falling weight center in the deflection basin. At this offset distance, the deflection of pavement under a fixed falling weight has been proved to depend only on the subgrade modulus and pavement thickness (overall thickness of the base layer and asphalt layer) [36,37]. As a result, the modulus of the subgrade layer is back-calculated by substituting the known inertial point and pavement thickness values. Models for calculating the inertial point and the deflection at this point have been developed, as shown in Eqs. (1) and (2):

$$R_{IP} = 255.7 + 19.07H - 192.9\ln(E_s) - 0.03198H^2 + 47.27(\ln(E_s))^2 - 4.695H\ln(E_s) - 0.0002024H^3 - 3.667(\ln(E_s))^3 + 0.3069H(\ln(E_s))^2 + 0.009718H^2\ln(E_s), \quad (1)$$

$$D_{IP} = 0.09944 + 15.24H^{-1} - 0.0721\ln(E_s) + 135.3H^{-2} + 0.01785(\ln(E_s))^2 - 5.313H^{-1}\ln(E_s) - 451.7H^{-3} - 0.001517(\ln(E_s))^3 + 0.4804H^{-1}(\ln(E_s))^2 - 17.39H^{-2}\ln(E_s), \quad (2)$$

where $R_{IP}$ is the offset distance corresponding to the inertial point (cm), $D_{IP}$ is the deflection at the inertial point (mm), $H$ refers to the pavement thickness (m), and $E_s$ represents the modulus of the subgrade layer.

The detailed back-calculation process of subgrade modulus $E_s$ is presented as Step ① of the flowchart in Fig. 1.

As seen in Fig. 1, the values of $R_{IP}$ and $D_{IP}$ are first calculated via Eqs. (1) and (2) for the assumed subgrade modulus. Then, the computed deflection $D_{IP}$ is compared

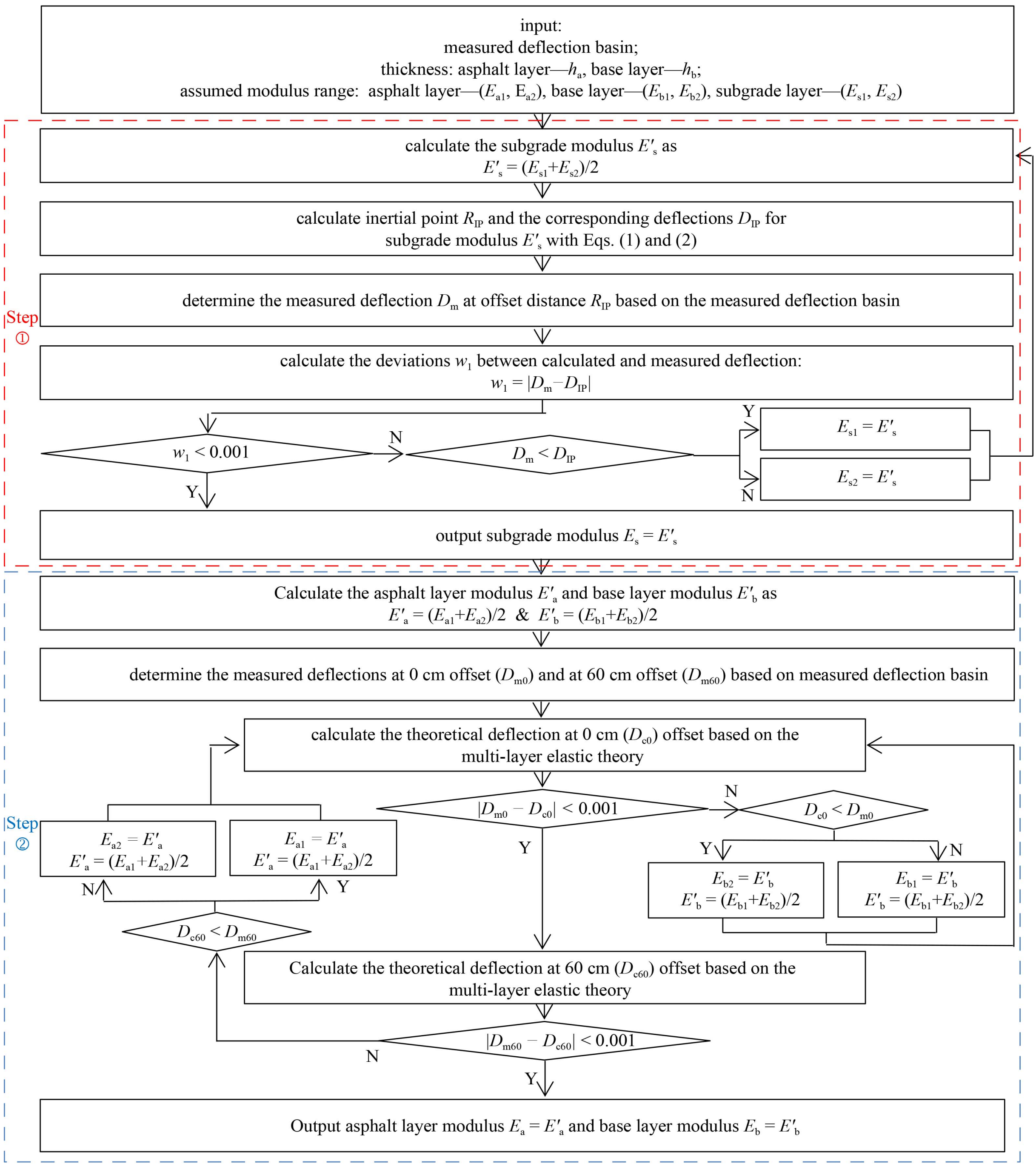



**Fig. 1** The flowchart of back-calculating layer modulus from the FWD deflection basin.

with the measured deflection at the offset distance $R_{IP}$. If their deviation falls within the tolerance limit, the assumed subgrade modulus is taken as the final back-calculated value. After that, two more deflection points within the deflection basin are required to back-calculate the base and asphalt layers' moduli. The deflections at 0 and 60 cm offset distances from the falling weight center are used for the back-calculation, as recommended by previous research work [36]. The detailed back-calculation procedures for base and asphalt layers' moduli are also presented in Fig. 1 and labeled as Step ②. Their determination principle is similar to that adopted for subgrade modulus, except that the theoretical reference deflections at 0 and 60 cm are established via the multi-layer elastic theory (MET), whereas the deflection at the inertial point is derived via Eq. (2).

The procedure depicted in Fig. 1 can generate a stable back-calculation result independent of the initial input layer moduli. Previous research [36] has compared the above procedure with some famous back-calculation softwares, including EVERCALC and MODULUS. The comparisons show that the present procedure is precise for the back-calculation of the asphalt layer modulus based on FWD test results. More discussions on the accuracy and reliability of this procedure will be presented in Section 3.2.

### 2.2 Procedure for determining asphalt layer modulus under vehicular loading mode

The modulus of the asphalt layer under vehicular mode is mainly controlled by temperature and vehicular speed. Temperature influences the asphalt binder's viscoelastic properties and, thus, the mixture's modulus. The vehicular speed influences the asphalt layer's modulus via loading frequency. A schematic diagram of the strain response pulse measured in the field asphalt layer under vehicular loading is presented in Fig. 2. It shows that the strain pulse lasts over a certain period, defined as the pulse loading time. An increase in the vehicular speed shortens the loading time and increases the loading frequency, which ultimately induces a higher asphalt layer modulus.

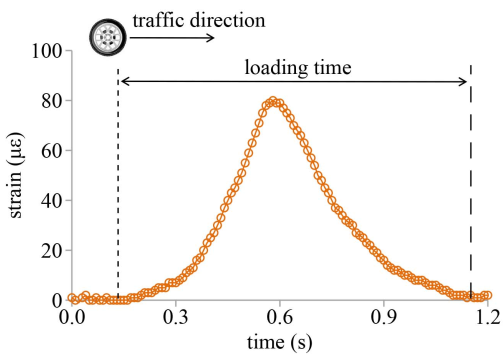



**Fig. 2** Schematic diagram of the asphalt layer's loading time corresponding to a single pass of vehicular loading.

This study adopts the procedure which has been earlier proposed by our research team [17,29], to construct the asphalt layer's modulus master curve induced by the vehicular mode. In the proposed procedure, the field-measured pavement strain data at various vehicular speeds and temperatures are incorporated to consider the influences of vehicular speed and temperature on the moduli of the asphalt layer. The detailed procedure is described in Fig. 3.

In the procedure, the loading frequency ($f$) of the asphalt layer under vehicular loading is first calculated based on the strain response pulse, which subprocess is referred to as Step ①. There are several alternative methods for deriving the loading frequency $f$ from the strain pulse shape, e.g., the fast Fourier transform (FFT) method, or via the loading time ($t$), e.g., $f = 1/(2\pi t)$ or $f = 1/t$ [1,3,39,40]. In this paper, the latter formula $f = 1/t$ is chosen, being the most consistent with the frequency defined in the laboratory loading tests. Besides, since this method has been adopted by the current MEPDG procedure to calculate the pavement frequency, the findings obtained via this method can be easily incorporated into the current design method for further applications.

Once the loading frequency is known, the asphalt layer modulus is back-calculated using the measured strains, as shown in the procedure labeled Step ② in Fig. 3. For the back-calculation process, the finite element (FE) method is used to calculate the theoretical strains of the asphalt layer. The input modulus of the FE pavement model is changed continually until the gap between the field-measured and calculated asphalt strains is minimal.

The procedure described in Fig. 3 yields the modulus values as well as the frequencies of field asphalt layer at various temperatures. Those modulus and frequency data are further applied to construct the asphalt layer's modulus master curve. The adopted sigmoid model fits the master curve via Eqs. (3) and (4):

$$\log E = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log \tau}}, \tag{3}$$

where $E$ refers to the stiffness modulus (Pa), $\alpha$, $\delta$, $\beta$, and $\gamma$ represent the fitting parameters, and $\tau$ represents the loading frequency (Hz) at the reference temperature. The frequencies for other temperatures are derived from $\tau$ by multiplying it to a shift factor $a_T$, which is calculated as follows [41]:

$$\lg a_T = \frac{-C_1 (T - T_{ref})}{C_2 + (T - T_{ref})}, \tag{4}$$

where $T_{ref}$ refers to reference temperature (°C), $T$ represents the temperature of interest (°C), $C_1$ and $C_2$ refer to the fitting parameters.

## 2.3 Procedure for determining asphalt layer modulus under laboratory loading modes

Three types of laboratory loading modes are adopted in this research to assess the stiffness modulus of asphalt mixture in the lab. They are the UC, 4PB, and IDT modes, respectively. The schematic diagrams for those loading modes are illustrated in Fig. 4.

For each loading mode, the continuous haversine loading pulse is applied, as shown in Fig. 5. As the inverse value of loading times, the loading pulse frequencies of 0.1, 0.5, 1, 5, 10, and 25 Hz are used. The test temperatures at −10, 4.4, 21.1, 37.8, and 54.4 °C are included. Strains of asphalt mixtures during the test are collected via the strain gauges, and used to derive the modulus of the mixture. In all loading modes, the maximum tensile strains of specimens are controlled below 100με as recommended by the AASHTO specification T 342-11, to ensure that the mixture stays within the linear viscoelastic domain.

With the proposed procedure, the laboratory modulus values of asphalt mixture under UC, 4PB, and IDT modes are obtained and fitted using Eq. (3) to construct the modulus master curves. The laboratory (UC, IDT, and 4PB) master curves are then compared with that obtained from the vehicular loading mode to evaluate their correlations, if any.

## 2.4 Correlating field and laboratory modulus of asphalt layer in the frequency domain

The asphalt modulus induced by vehicular load is directly used in pavement design and assessment, while those obtained in FWD and laboratory loading modes need to

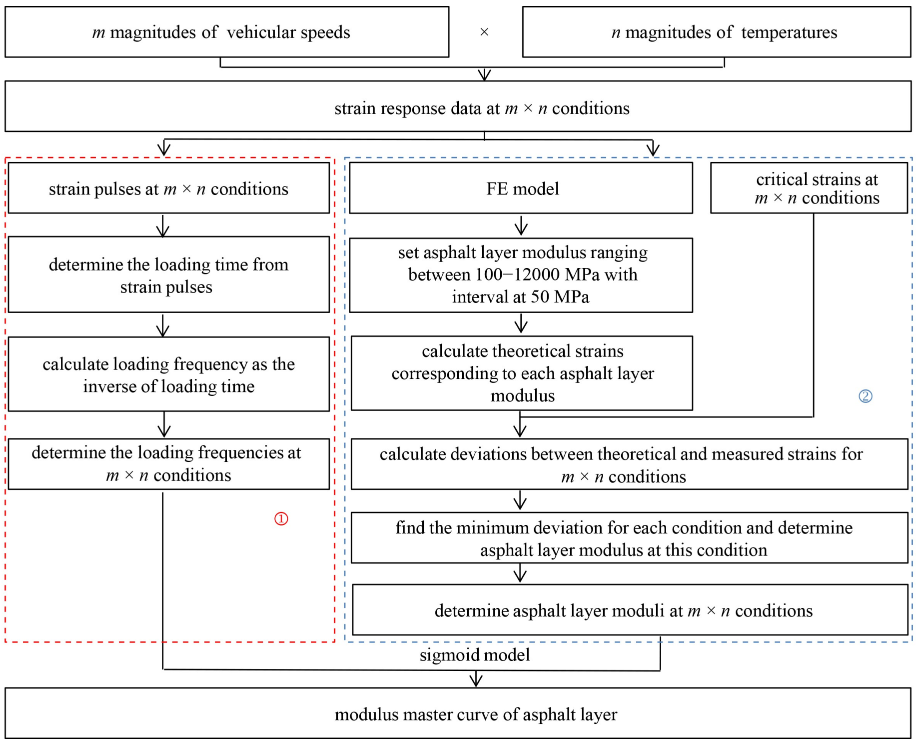



**Fig. 3** The flowchart for constructing the asphalt layer's modulus master curve.

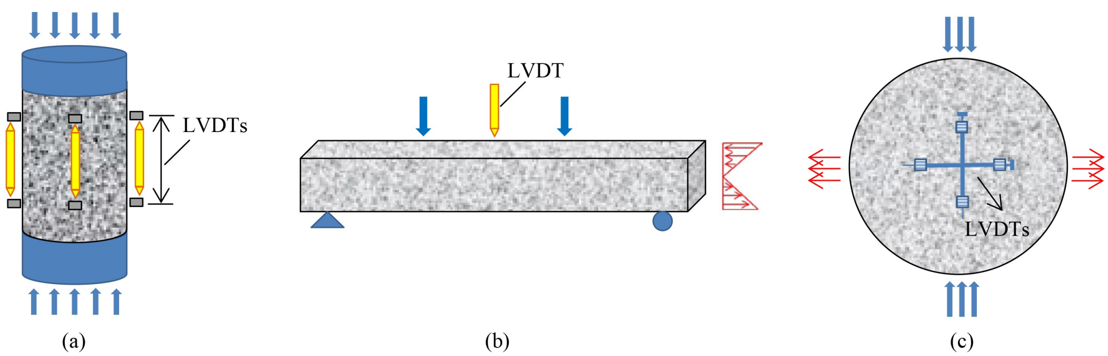



**Fig. 4** Schematic diagrams for the (a) UC, (b) 4PB, and (c) IDT laboratory loading modes.

be correlated with the former one, to facilitate their applications in the design and assessment procedures. In the present research, loading frequency is applied as an intermediary parameter for correlating asphalt layer modulus under differing loading modes. As shown in Figs. 2 and 5, the frequencies of vehicular and laboratory loadings are determined as the reciprocal of loading pulse duration. For FWD loading, the same frequency calculation method is used. As depicted in Fig. 6, a typical FWD loading pulse is stable within the loading period of approx. 0.03 s. Consequently, the respective frequency of 33.33 Hz (i.e., 1/0.03 s) is adopted.

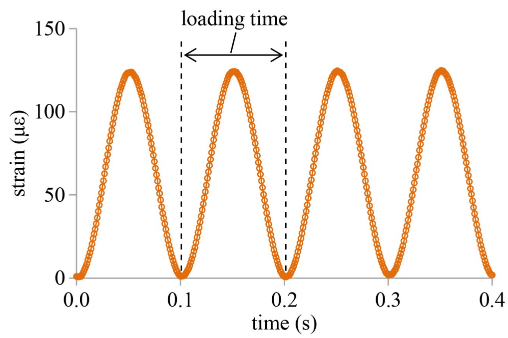



**Fig. 5** Schematic diagram of the loading pulse in laboratory modulus tests.

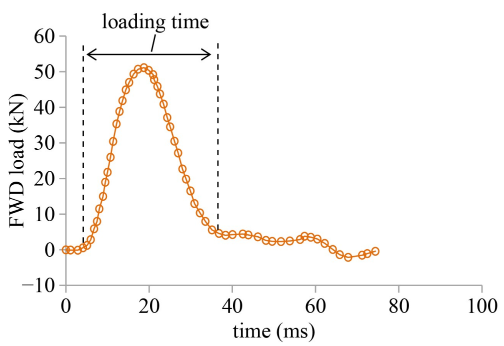



**Fig. 6** Schematic diagram of loading time of FWD loading pulse.

As the frequencies corresponding to the above loading modes are obtained, the asphalt layer moduli under those modes are compared in the frequency domain, and their correlations are established.

## 3 Demonstration of the proposed approach

### 3.1 Field and laboratory test data acquisition

The above approach for determining and correlating the asphalt layer's modulus values under different modes is applied to the data collected from two full-scale pavements. The pavement structures of the two test sections are depicted in Fig. 7. It is seen that one section uses the semi-rigid pavement structure while the other one adopts the flexible pavement structure.

As shown in Fig. 7, the asphalt and base layers in both pavements have thicknesses of 30 and 35 cm, respectively. Both pavements have identical asphalt layers (AC-13 mix) and subgrade layers. Still, their base layers are different, namely with cement-stabilized macadam in the semi-rigid pavement and with unbound granular material in the flexible one. The asphalt binder used in the AC-13 mixture has a penetration grade of 60/70. The asphalt binder properties are summarized in Table 1, while the Marshall properties and aggregate gradation of the mix are shown in Table 2 and Fig. 8, respectively.

Strain and deflection data of test sections were measured using the vehicular and FWD loading tests, respectively. In vehicular loading tests, Tokyo Sokki KMS-100 strain gauges are utilized to monitor the pavement strain responses. As shown in Figs. 7(a) and 7(b), strain gauges are settled at 13 and 24 cm depths of semi-rigid pavement, and are installed at 6 and 30 cm (bottom) of flexible pavement. At each depth, two gauges are oriented in the transverse direction, while two are oriented in the longitudinal direction, as shown in Fig. 7(c).

A full-scale vehicular load simulator named MLS 66, as shown in Fig. 9(a), is used for applying vehicular loading. Four asphalt layer heaters with set temperatures of 15, 25, 35, and 45°C are incorporated into the

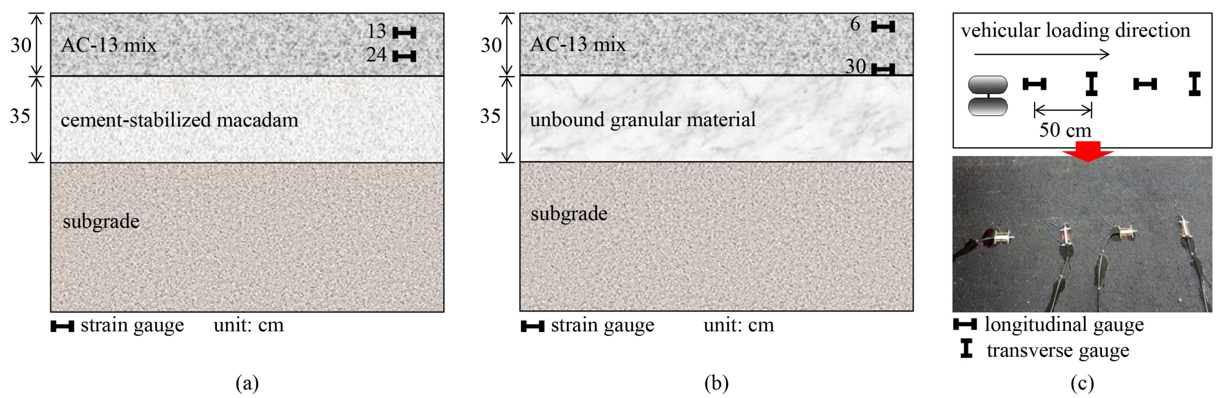



**Fig. 7** (a) The semi-rigid and (b) flexible pavement test section structures, and (c) the layout of strain gauges.

experimental setup. Four wheel motion speeds (i.e., vehicular speeds) of 22, 16.5, 11, and 5.5 km/h are performed for each pavement temperature condition. The FWD loading test is conducted using a Primax FWD facility depicted in Fig. 9(b). The FWD loading tests involve three asphalt layer temperatures, namely 15, 25, and 35 °C. Six repeated FWD tests are conducted at 25 °C, and two more are done, one at 15 °C and one at 35 °C. In both FWD load tests and vehicular load tests, the applied loading magnitude is 50 kN.

The measured deflection and strain data are used to determine the moduli of asphalt layer under field loading modes (FWD mode and vehicular mode) using the procedures depicted in Figs. 1 and 3. Despite field tests, laboratory tests are performed to obtain asphalt mixture modulus under three laboratory loading modes (UC, IDT, and 4PB), following the procedures described in Section 2.3. The samples used in UC, IDT and 4PB tests are made in the laboratory using the same mixtures as those in field experimental pavements (i.e., AC-13). For each loading mode, at least three parallel asphalt mixture specimens are used. The test equipment and specimens used in the laboratory UC, 4PB, and IDT loading modes are shown in Fig. 10.

**Table 1** The asphalt binder properties

| properties | unit | value |
|---|---|---|
| penetration (25 °c, 100 g, 5 s) | 0.1 mm | 66 |
| ductility (5 cm/min) | cm | > 100 (15 °C) |
| softening point | °C | 49.2 |
| mass loss after RTFOT | % | 0.08 |
| residual penetration ratio after RTFOT | % | 75.2 |
| ductility after RTFOT | cm | 23.3 |

Note: The RTFOT refers to the Rolling Thin Film Oven Test.

**Table 2** Properties of the AC-13 mixture

| properties | unit | results |
|---|---|---|
| asphalt content | % | 5.1 |
| density | g/cm$^3$ | 2.432 |
| air voids | % | 3.3 |
| voids filled with asphalt | % | 77.6 |
| voids in mineral aggregate | % | 14.7 |
| marshall stability | kN | 10.6 |

### 3.2 Asphalt layer modulus under field and laboratory loading modes

#### 3.2.1 Modulus of asphalt layer under field FWD mode

The deflection basins of two pavement sections (flexible and semi-rigid pavements) measured in FWD tests are summarized in Table 3.

It can be seen from Table 3 that the measured deflections rise with the increasing temperatures for both pavements. This fact implies the viscoelastic behaviors of the asphalt mixture layers. Based on those measured deflection data, the moduli of asphalt layers in two pavements are back-calculated following the program in Fig. 1. The detailed asphalt layer moduli at different temperatures are depicted in Fig. 11.

As expected, the back-calculated modulus values of asphalt layers of both pavements decrease with the temperature, and their moduli at the same temperature nearly coincided. The latter observation is in consistent with the fact that both pavements use the identical asphalt mixture. To further illustrate the accuracy of this back-

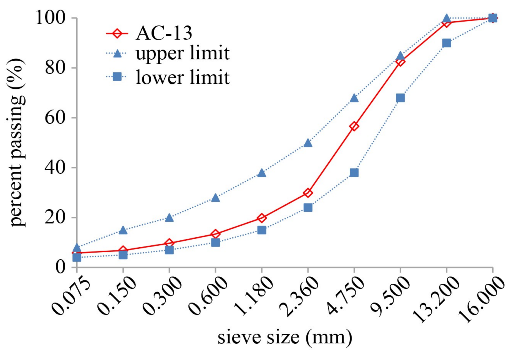
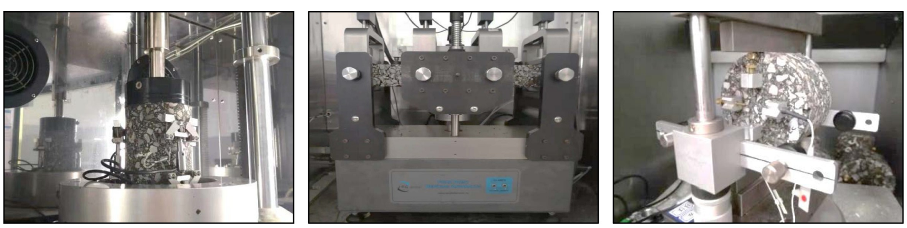



**Fig. 8** The aggregate gradation curve of the mix.

(a) (b)

**Fig. 9** (a) The MLS66 and (b) Primax FWD test facilities.



(a) (b) (c)

**Fig. 10** The experimental setup and specimens used in laboratory test modes: (a) UC, (b) 4PB, and (c) IDT.

**Table 3** The deflections of semi-rigid and flexible pavements at different temperatures in FWD tests (0.01 mm)

| pavement type | temperature (°C) | offset from the falling weight center in the deflection basin | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 cm | 20 cm | 30 cm | 45 cm | 60 cm | 90 cm | 120 cm | 150 cm | 180 cm | 210 cm |
| flexible | 15 | 115.8 | 97.0 | 90.4 | 80.7 | 71.9 | 63.7 | 56.6 | 43.9 | 34.2 | 27.1 |
| | 25 | 135.4 | 118.0 | 105.4 | 90.3 | 77.7 | 61.2 | 53.1 | 40.1 | 30.5 | 24.1 |
| | 35 | 253.6 | 187.7 | 155.6 | 113.4 | 91.5 | 75.6 | 65.0 | 48.2 | 36.6 | 28.8 |
| semi-rigid | 15 | 48.4 | 40.0 | 38.5 | 33.3 | 32.8 | 28.4 | 27.7 | 25.0 | 22.2 | 20.6 |
| | 25 | 58.4 | 43.0 | 39.5 | 36.2 | 34.7 | 29.6 | 28.5 | 26.0 | 23.2 | 20.9 |
| | 35 | 129.8 | 64.8 | 52.0 | 46.8 | 42.4 | 35.5 | 32.6 | 29.6 | 23.4 | 21.3 |

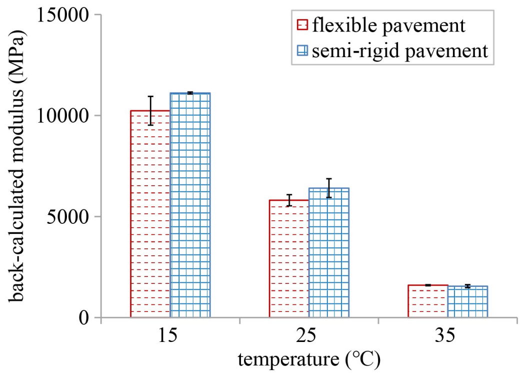



**Fig. 11** The back-calculated asphalt layer moduli of the two pavements.

calculation procedure, the theoretical deflection basins generated by the procedure are contrasted with the field-measured ones. The comparison results are shown in Fig. 12. It is seen that the deflection basins from the back-calculation procedure fit well with the measured ones, regardless of temperature and pavement types. This confirms that the back-calculation procedure used in this research is accurate enough to simulate deflections of field asphalt pavement.

### 3.2.2 Modulus of asphalt layer under vehicular loading mode

In vehicular loading tests, the strain responses of two experimental pavements are measured. The exemplary strain response pulses of semi-rigid and flexible pavements are plotted in Fig. 13. Noteworthy is that those characteristic strain pulses are collected with the vehicular speed of 11 km/h and the pavement temperature of 35 °C.

The measured strain response data are used to construct the modulus master curve of the asphalt mixture layer under vehicular load, following the procedure presented in Fig. 3. As shown in Step ① of Fig. 3, the loading frequency within the asphalt layer is first calculated based on the duration of the strain response pulse. Following the procedure, the loading frequencies for the two pavements are calculated and are summarized in Table 4. It should be noted that the frequencies in Table 4 are the averaged

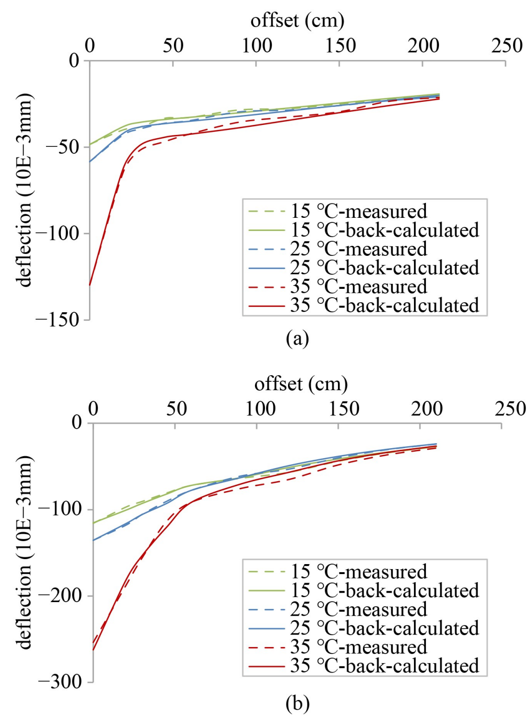



**Fig. 12** Comparison of the field-measured and theoretical deflection basins of (a) semi-rigid pavement and (b) flexible pavement.

frequencies determined from the four types of strain pulses (2 depths × 2 directions). The corresponding coefficients of variation (CoVs) of computed frequencies are also listed in Table 4 as numbers in brackets.

As seen in Table 4, the frequency within the pavement induced by vehicular loading is dependent on both vehicular speed and pavement temperature. The vehicular speed effect on loading frequency is much stronger than the temperature effect. A rise in vehicular speed or temperature increases the loading frequency. For the same combination of temperature and vehicular speed, the loading frequency within the flexible pavement resembles that in the semi-rigid one. This may be because these two pavements have the same type of asphalt layer. Therefore, the loading frequencies calculated for the two pavements are averaged and then used to fit the model for estimating the asphalt layer frequency. The established

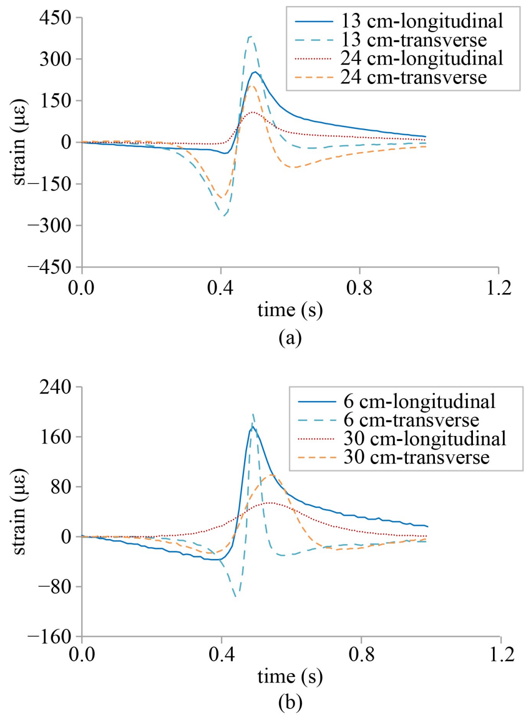



**Fig. 13** Exemplary strain response pulses of (a) semi-rigid pavement and (b) flexible pavement.

**Table 4** Loading frequencies (Hz) and CoVs of the frequencies of two pavements under various vehicular speeds and pavement temperatures

| pavement type | vehicular speeds (km/h) | temperature | | | |
|---|---|---|---|---|---|
| | | 15 °C | 25 °C | 35 °C | 45 °C |
| flexible | 5.5 | 0.70 (0.25) | 0.84 (0.24) | 0.81 (0.30) | 1.09 (0.44) |
| | 11 | 1.42 (0.23) | 1.60 (0.17) | 1.89 (0.30) | 2.18 (0.42) |
| | 16.5 | 2.14 (0.24) | 2.37 (0.13) | 2.76 (0.26) | 3.09 (0.42) |
| | 22 | 2.96 (0.24) | 3.19 (0.12) | 3.92 (0.37) | 4.40 (0.38) |
| semi-rigid | 5.5 | 0.73 (0.12) | 0.69 (0.08) | 0.97 (0.14) | 1.16 (0.19) |
| | 11 | 1.43 (0.14) | 1.38 (0.12) | 2.06 (0.10) | 2.45 (0.17) |
| | 16.5 | 2.33 (0.10) | 1.94 (0.10) | 3.16 (0.16) | 3.33 (0.18) |
| | 22 | 3.00 (0.15) | 2.88 (0.08) | 4.41 (0.13) | 5.09 (0.28) |

Note: numbers in brackets indicate CoVs of computed frequencies

prediction model for the loading frequency, $f$(Hz) is given as follows:

$$f = 0.0984e^{0.0160T} \cdot V \quad (R^2 = 0.991), \tag{5}$$

where $V$ refers to the vehicular speed (km/h), and $T$ represents the pavement temperature (°C). Noteworthy is that Eq. (5) is established based on the strain response data measured at relatively low vehicular speed. Accordingly, it may need verification by the data collected at higher vehicular speed conditions.

After the loading frequency was determined, the modulus of asphalt layer under vehicular load is then back-calculated from the critical strains (i.e., the maximum tensile/compressive strains) in the strain pulse following the Step ② of Fig. 3. In the back-calculation process, the FE model of field pavement is developed and used to calculate theoretical strains of asphalt layer. The developed FE model is shown in Fig. 14. The structural layers in the FE model are identical to those in field pavements. The vehicular loading mode is realized by shifting the loading area in the model with a specific motion speed. The element dimension in the loading area is 0.044 m × 0.015 m × 0.088 m. Outside the loading area, the element mesh becomes relatively coarse to increase the calculation speed. The element type is C3D8I. The infinitely large elements (CIN3D8) are applied around the model to simulate the boundary condition of the pavement.

Combing the measured strains and the developed FE model, the moduli of the asphalt layer under different temperature and vehicular speed conditions are back-calculated, using the procedure depicted in Section 2.2. Figure 15 displays the modulus back-calculation results. Besides, to evaluate the feasibility of FE model for field strain simulation, the calculated strains from the FE model are plotted against the measured strains in Fig. 16.

Figure 15 reveals that the asphalt layer modulus of both pavement types increases with vehicular speed and declines with temperature, implying the viscoelastic properties of the asphalt mixture. Simultaneously, the modulus values of the asphalt layer in flexible pavement are close to those in semi-rigid pavement, which is consistent with the point that asphalt mixture layers used in two pavements are the same. Figure 16 shows that the strains calculated via the FE model fit well with the field-measured ones. This proves the reliability of the adopted FE model for field pavement response simulation.

Based on Eq. (5), the loading frequencies within the asphalt layer are predicted from the vehicular speeds in Fig. 15. Thus, the moduli and frequencies of the asphalt layer under different temperature conditions are determined. Then, Eq. (3) is applied to fit those modulus and frequency data, to generate the modulus master curve. The developed master curve containing the averaged results from flexible and semi-rigid pavements is shown in Fig. 17. With the help of the developed master curve, the asphalt layer modulus under vehicular loading mode

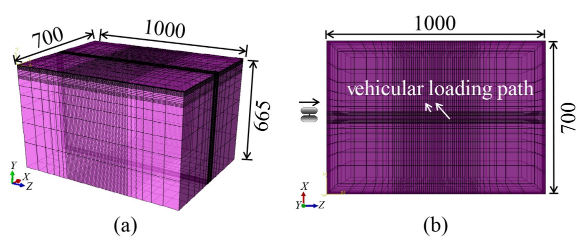



**Fig. 14** (a) The overall view and (b) plan view of the FE pavement model (unit: mm).

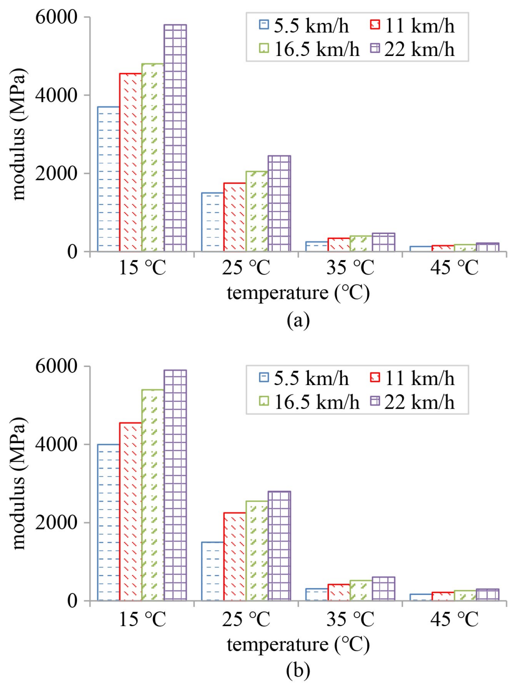



**Fig. 15** The back-calculated moduli of asphalt layer of (a) semi-rigid pavement and (b) flexible pavement under vehicular load.

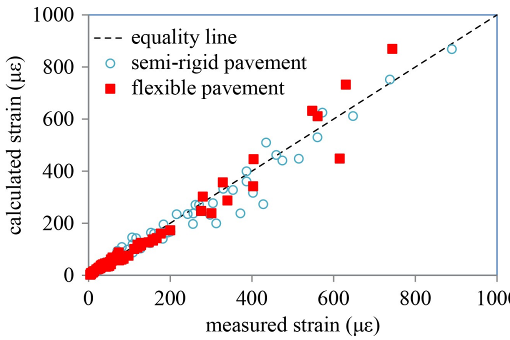



**Fig. 16** FEM-calculated and measured strains for semi-rigid and flexible pavements.

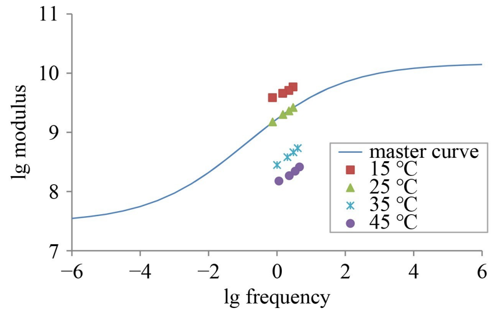



**Fig. 17** The fitted modulus master curve of the asphalt layer induced by the vehicular load.

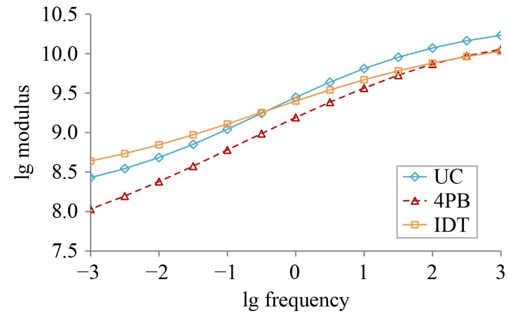



**Fig. 18** The modulus master curves of asphalt mixture under UC, 4PB, and IDT modes.

can be estimated in a wide frequency (vehicular speed) domain and temperature domain.

### 3.2.3 Modulus of asphalt layer under laboratory loading modes

The laboratory UC, IDT, and 4PB tests are performed to evaluate the asphalt layer modulus under laboratory loading mode. The detailed test procedures are discussed in Section 3.1. Based on the test results, the modulus master curves of the asphalt mixture under UC, IDT, and 4PB modes are developed using Eq. (3), and are shown in Fig. 18.

As shown in Fig. 18, considerable deviations exist between the modulus master curves obtained from the different laboratory loading modes. The modulus tested under UC mode apparently exceeds that tested under 4PB mode over a wide frequency range. As discussed, the measurements from UC mode mainly represent compressive modulus property of the mixture. By contrast, the specimen in 4PB mode is subjected to compressive and tensile stresses simultaneously. Accordingly, the 4PB test results reflect the combined compressive and tensile moduli of the material. Therefore, the comparisons between the UC and 4PB moduli, to some extent, reveal that the tensile modulus of the mixture is lower than the compressive one. Indeed, the above finding has also been verified by other researchers, who have stated that the asphalt mixture’s compressive modulus is higher than its tensile modulus in the compression-tension complex modulus test [11,12,14].

The IDT modulus, theoretically, also presents the combined compressive-tensile property of the mixture. However, it can be observed that the IDT modulus resembles better the UC modulus than the 4PB modulus. This may be because the compressive stress of the specimen under IDT mode exceeds the tensile stress [21]. As a result, the IDT test results dominantly reveal the compressive modulus property of the material.

## 3.3 Correlating the asphalt layer modulus under field and laboratory loading modes in the frequency domain

As the master curves of asphalt mixture moduli under vehicular and laboratory modes are obtained, they are directly compared in the frequency domain. The comparison of results is illustrated in Fig. 19.

Figure 19 shows apparent deviations between the master modulus curves from laboratory UC mode and vehicular loading mode. The asphalt layer modulus measured in the UC mode is significantly larger than that under vehicular loading mode for the same frequency. The UC test has been widely applied in the current design methods for determining asphalt layer modulus. However, this study's findings strongly indicate that the UC mode overestimates the modulus of the asphalt pavement layer under vehicular load. Therefore, the application of UC test results in pavement design would underpredict the pavement responses and generate a non-conservative design outcome. The modulus master curve from IDT test also deviates from that under vehicular load in a wide frequency range. As for the 4PB mode, it is exciting to observe that the master curve from this mode is quite close to that of the vehicular loading mode. The above observation implies that the 4PB mode is better than the UC and IDT modes at simulation of the vehicular load. This may be attributed by the fact that the field asphalt layer behaves like a large-scale bending beam under the vehicular load, just as the mixture behaves under the laboratory 4PB mode.

The preceding discussions suggest that the laboratory 4PB modulus resembles the modulus of asphalt layer under vehicular load. As a result, the 4PB mode is recommended for determination of the asphalt mixture's modulus for pavement design. In contrast, the moduli determined in the UC and IDT modes need to be adjusted to simulate vehicular loading conditions. The adjustment factors, defined as the ratios of the asphalt layer moduli induced by the vehicular load to the moduli induced by the UC/IDT mode, are calculated using the master curve models (as shown in Fig. 20). The calculated adjustment factors of UC/IDT moduli at wide temperature and frequency ranges are presented in Fig. 20. Clearly, the adjustment factors are highly dependent on the pavement temperature conditions, with their values descending with the rise of the temperature. As the pavement temperature exceeds 35 °C, the adjustment factors reach values below 0.4, indicating that the UC and IDT moduli obviously overestimate the asphalt layer moduli in high-temperature scenarios.

To facilitate the application, the UC/IDT-related adjustment factors for several frequently used temperatures and frequencies in the pavement design process are further presented in Table 5. Noteworthy is that the numbers in brackets with an italics type indicate the adjustment factors of IDT moduli, while the numbers with a regular style refer to the factors of UC moduli. Based on these adjustment factors, the UC and IDT moduli could be refined to simulate the asphalt layer moduli induced by vehicular loading more accurately.

The correlations between the asphalt layer moduli under FWD load with those under laboratory and vehicular loadings are also established using the master curves. As mentioned earlier, the stable FWD loading frequency is 33.33 Hz. Therefore, by substituting $f$ = 33.33 Hz and the test temperatures into the master curves from laboratory 4PB loading and vehicular loading, the asphalt layer moduli induced by FWD load are calculated. Those predicted moduli were then compared with the actual asphalt moduli (the back-calculation results shown in Fig. 11) under the FWD load. The respective results are plotted and compared in Fig. 21.

As shown in Fig. 21, the moduli derived from the modulus master curves closely fit the actual asphalt

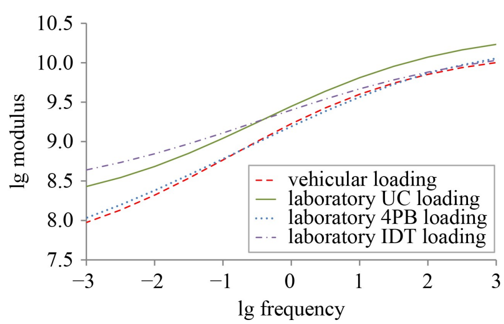



**Fig. 19** The asphalt layer moduli under three loading modes in the frequency domain.

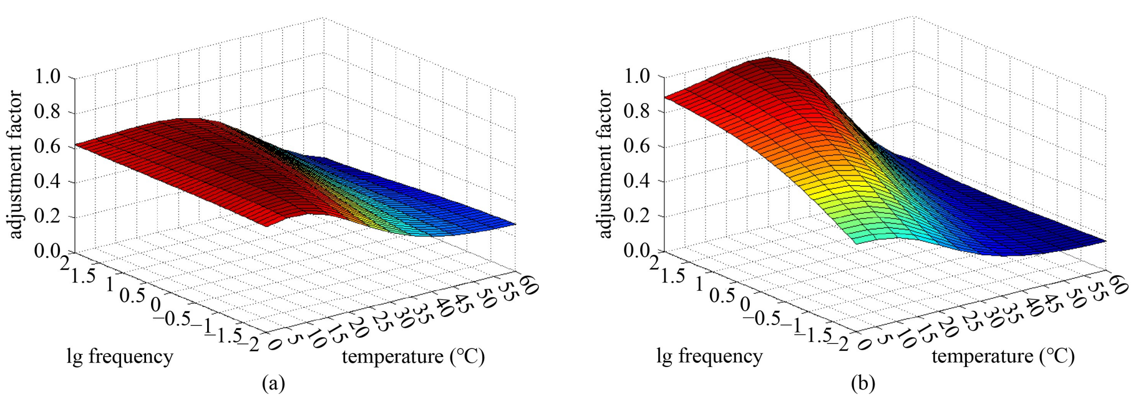



**Fig. 20** Adjustment factors of (a) UC and (b) IDT test moduli.

**Table 5** The modification factors of UC moduli and IDT moduli at several frequently used temperatures and frequencies

| frequency (Hz) | temperature | | | | | |
|---|---|---|---|---|---|---|
| | 5 °C | 10 °C | 15 °C | 20 °C | 25 °C | 30 °C |
| 1 | 0.63 (0.80) | 0.65 (0.81) | 0.66 (0.81) | 0.64 (0.76) | 0.60 (0.67) | 0.53 (0.54) |
| 5 | 0.68 (0.85) | 0.64 (0.88) | 0.65 (0.89) | 0.64 (0.88) | 0.62 (0.81) | 0.56 (0.69) |
| 10 | 0.63 (0.87) | 0.64 (0.90) | 0.64 (0.92) | 0.64 (0.91) | 0.62 (0.86) | 0.57 (0.75) |
| 25 | 0.62 (0.89) | 0.63 (0.91) | 0.64 (0.94) | 0.64 (0.94) | 0.62 (0.91) | 0.58 (0.83) |

Note: numbers in brackets indicate the adjustment factors of IDT moduli.

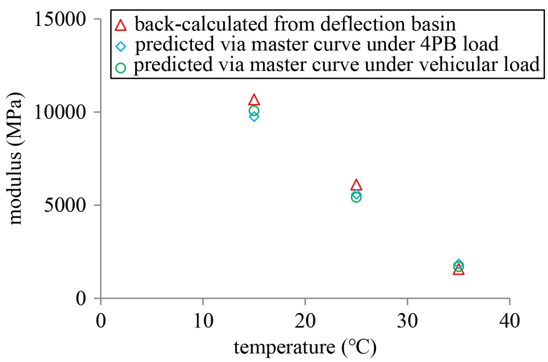



**Fig. 21** Comparison of asphalt layer moduli derived from modulus master curves with the actual moduli (the back-calculated moduli).

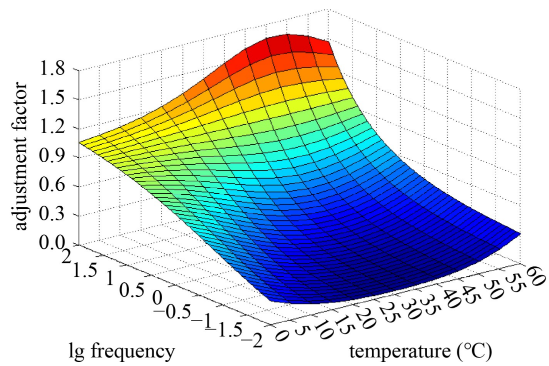



**Fig. 22** Adjustment factors of FWD moduli at different design temperatures and frequencies.

moduli that back-calculated from the deflection basins, with their average deviation being 9.75%. Since the master curves from 4PB and vehicular modes nearly coincide in Fig. 19, they provide nearly identical prediction results. The above fact implies that the master curves from 4PB and vehicular modes work well for estimating the asphalt layer modulus under FWD load, with the FWD-induced frequency (33.33 Hz) as the input frequency parameter. As a result, the modulus of the asphalt layer induced by FWD mode is also closely correlated with that under vehicular and 4PB modes within the particular frequency domain.

The FWD-induced frequency (33.33 Hz) is larger than that induced by the typical vehicular loading (as seen from Table 4). Hence, the asphalt layer modulus obtained in FWD load also needs adjustment before its application in pavement rehabilitation design or pavement assessment. The adjustment factor for FWD modulus is derived as the ratios of asphalt layer modulus induced by the vehicular frequencies to that by FWD frequency. The modulus values under vehicular and FWD frequencies are both calculated using the developed master curve in Fig. 19. Subsequently, the adjustment factors of FWD moduli are determined and are presented in Fig. 22. Figure 22 reflects that the adjustment factors vary greatly with the changing vehicular loading frequencies. As the loading frequency rises, the adjustment factor approaches 1.0. This trend further verifies that the FWD loading mode is better suited to simulate the modulus property of asphalt layer under a high-loading-frequency scenario.

Similarly, for some frequently used loading temperatures and frequencies, the corresponding adjustment factors are presented in Table 6. With those factors, the modulus data obtained in the FWD mode could be adjusted to represent the asphalt layer modulus under vehicular loading mode.

**Table 6** The modification factors of FWD moduli at several frequently used temperatures and frequencies

| frequency (Hz) | temperature | | | | | |
|---|---|---|---|---|---|---|
| | 5 °C | 10 °C | 15 °C | 20 °C | 25 °C | 30 °C |
| 1 | 0.65 | 0.56 | 0.46 | 0.37 | 0.29 | 0.24 |
| 5 | 0.83 | 0.77 | 0.71 | 0.63 | 0.56 | 0.49 |
| 10 | 0.90 | 0.86 | 0.82 | 0.76 | 0.70 | 0.65 |
| 25 | 0.98 | 0.97 | 0.96 | 0.94 | 0.93 | 0.91 |

### 3.4 Overview of the developed approach

The procedures described in the preceding sections are used to elaborate the general approach to bridge the gaps between the modulus of asphalt layer under field and laboratory loading modes. The overall framework of the proposed approach is presented in Fig. 23.

Figure 23 illustrates how the loading frequency is established as the intermediary parameter to correlate the asphalt layer modulus determined via three conventional loading modes. The asphalt layer modulus obtained via any loading mode is applied properly to predict the one applicable for pavement design: the laboratory 4PB mode satisfactorily characterized the asphalt mixture modulus

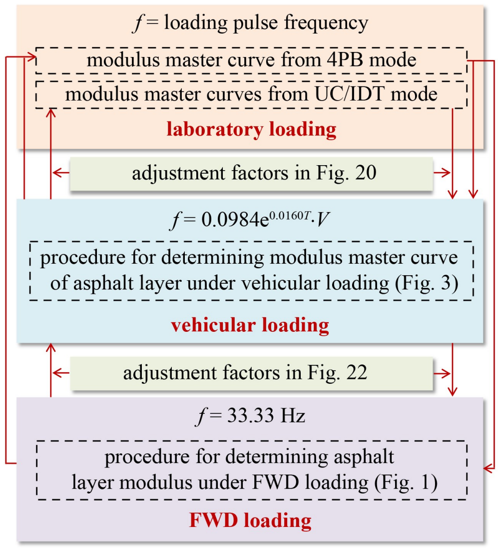



**Fig. 23** The correlations of asphalt layer moduli obtained via different conventional loading modes.

under vehicular load. In contrast, the asphalt layer moduli obtained in UC, IDT, and FWD loading modes are adjusted to simulate the asphalt layer modulus under vehicular load effectively. The corresponding adjustment factors are plotted in Figs. 20 and 22.

The limitation of this approach is that the data come from only two experimental pavements owing to the high construction cost and operation cost of the large-scale test section. In addition, the pavements under study use an uncommon asphalt layer combination (i.e., 30-cm AC-13 asphalt mixture). As a result, additional test data from other experimental sites are needed to further validate and refine the research findings. Nevertheless, this research has developed a set of concepts and methods for the validation and refinement work.

## 4 Conclusions

This study proposes a comprehensive approach for correlating the modulus values of asphalt layer induced by different laboratory and field modes for pavement design and assessment. In the developed approach, the loading frequency is used as a key parameter for the correlation analysis. The main findings included in the approach are shown as follows.

1) The modulus master curve constructed in the laboratory 4PB mode closely matched the vehicular loading mode. Thus, the modulus measured in 4PB tests is preferred to characterize the modulus property of the asphalt layer in pavement design.

2) The laboratory UC mode overestimated the asphalt layer moduli of the vehicular loading mode, resulting in a non-conservative pavement design. The IDT test modulus also deviated from that under vehicular loading. The respective adjustment factors were calculated in this research to facilitate the applications of UC/IDT moduli for field condition characterization.

3) The moduli of asphalt layer induced by two field modes (vehicular, FWD) and one laboratory mode (4PB) were closely correlated in the studied frequency domain. The asphalt layer modulus obtained from one of the above loading modes can predict the moduli at other modes. The frequency of FWD loading (33.33 Hz) exceeded that in vehicular loading, implying that the asphalt layer modulus back-calculated from the FWD mode also needed adjustment before its application to pavement design and assessment. The corresponding adjustment factors were calculated in this study.

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