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Modulus attenuation of semi-rigid asphalt pavement layer in accelerated pavement testing with MLS66

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A B S T R A C T

This research aimed to investigate the attenuation mode of the layer modulus of asphalt pavement in accelerated pavement testing (APT). A full-scale experimental section was constructed and tested using the APT facility. Two non-destructive testing (NDT) methods, named falling weight deflectometer (FWD) technique and portable seismic property analyzer (PSPA) test, were used to obtain the layer moduli of asphalt pavement during the APT test. The variation patterns of layer moduli obtained by FWD and PSPA tests were calculated and compared after the temperature was corrected to 20 ℃. It was found that the variation pattern of surface layer modulus based on field FWD measurements was consistent with the one measured from PSPA tests. That is the modulus of the surface layer increases with the APT load repetitions firstly and then decreases with the rise of the repetitions. The modulus values of the surface layer measured from PSPA tests are obviously larger than those backcalculated based on deflection basins. The ratio of the measured surface layer modulus based on the PSPA test to the backcalculated one based on the FWD test ranges between 2.06 and 2.71. The backcalculated base layer modulus always declines with the increasing loading repetitions. The attenuation patterns of the surface layer modulus and the base layer modulus in the damage stage are described as $E_a = 421100 * N^{-0.6119}$ and $E_b = 128000 * N^{-0.1096}$, respectively.

1. Introduction

The evaluation of the load-carrying capacity of the in-service asphalt pavement structure should be implemented to guide maintenance and rehabilitation. The evaluation methods can be divided into destructive and non-destructive categories (Sun, 2013). Among destructive testing, the common method is to drill the core samples from the pavement structure and measure the performance parameters through general mechanical experiments. However, this commonly applied way will damage the consistency of the pavement and waste time (Wu et al., 2015). Recently, the non-destructive testing (NDT) has been increasingly used for evaluating the condition of the pavement layer. Backcalculating the layer modulus from the falling weight deflectometer (FWD) data is one of the popular NDT methods (Huang and Deng, 1996; Smith et al., 2017). FWD test has been used worldwide due to its advantages of relatively rapid, high efficiency, and non-destructive character-

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istic. In the FWD tests, deflection basins are measured by several sensors at the surface of the layer. All the layer moduli of a pavement structure can be calculated based on the deflections using a backcalculation method.

In the past, much research has been conducted on the modulus backcalculation methods based on the deflection data. The current backcalculation methods can be divided to 2 categories. One is the algorithm based on the deflection basin matching, including regression equations, iterative method, database method, mathematical programming method (Meier et al., 1997; Roque et al., 1998; Saltan et al., 2011; Wang et al., 2020; Zihan et al., 2020; Mehta and Roque, 2003; Ji et al., 2002; El-Raof et al., 2018; Fwa and Rani, 2005; Varma et al., 2013), which can be called the basin matching algorithm. The principle of the algorithm is to find a set of moduli that the theoretical deflection and the measured deflection have the highest matching degree in a specified tolerance. The other is the algorithm based on the deflection basin regulation to backcalculate the layer moduli (Zhang and Sun, 2004a; Sun et al., 2001; Zhu and Sun, 2017). It can be decomposed into the inertial point method which is used to backcalculate the subgrade modulus and the identity point method which is used to backcalculate the moduli of the surface and base layer. Compared with the basin matching algorithm, the deflection basin regulation algorithm has the advantage of generating a unique and more reasonable backcalculation solution (Zhang and Sun, 2004b; Zang et al., 2017). In this study, the layer moduli are backcalculated using the deflection basin regulation algorithm.

With the introduction of electrical, thermal, and acoustic technologies into the evaluation of the load-carrying capacity, the portable seismic wave analyzer (PSPA) test has also been used to measure the pavement modulus non-destructively (Celaya and Nazarian, 2007; Azari et al., 2014). The PSPA test measure the surface layer modulus based on the seismic wave theory, which can be called seismic modulus. PSPA test is widely used because it is cheap and non-invasive for the pavement (Bell et al., 2012; Jurado et al., 2012). Also, the variability of the measured moduli is small enough to be accepted (Oh and Fernando, 2011). However, the high loading frequency has been generated by the PSPA test and it needs to close traffic during the test. Moreover, with the development of deflection detection equipment, the appearance of testing system of laser high speed deflectometer makes the deflection test do not need to close traffic. This heavily enhances the practicality of backcalculating moduli based on FWD deflections. Although the FWD and PSPA test have become more common pavement evaluation methods, there is few studies on the relationship between the backcalculated surface modulus and measured seismic modulus. It is necessary to study the relationship between the backcalculated modulus and the seismic modulus to better evaluate the load-carrying capacity of the pavement structure.

Accelerated pavement testing (APT) is an effective way in simulating the real traffic loading on in-service asphalt pavement. It can achieve long-term pavement performance in a short time. In recent years, it is often used to evaluate the traditional fatigue properties and rutting resistance of field asphalt pavements (Sirin et al., 2008; Yeo et al., 2008; Ji et al., 2013; Ma et al., 2019). However, there are few studies on the layer moduli attenuation mode of asphalt pavement in the APT test.

The objective of this study is to study the relationship between the backcalculation modulus and the seismic modulus and investigate the attenuation mode of the layer moduli of asphalt pavement in the APT test. A full-scale experimental section was constructed and tested using the APT facility. Two NDT methods, named FWD and PSPA test, were used to evaluate the layer modulus of asphalt pavement during the APT test. The variation patterns of layer moduli based on the FWD and PSPA test were evaluated and compared to explore the relationship between the two types of layer modulus.

2. Experimental tests

A full-scale experimental asphalt pavement testing with MLS66 was constructed. The pavement structure was a typical semi-rigid base pavement, which was shown in Fig. 1(a). The surface layer of the pavement structure is 30 cm thickness AC13, which is widely applied in China. The pavement structure was compacted by different compaction machines. The asphalt and air contents of the asphalt mixture were 4.8% and 4.2%, respectively. The gradation of the AC13 is shown in

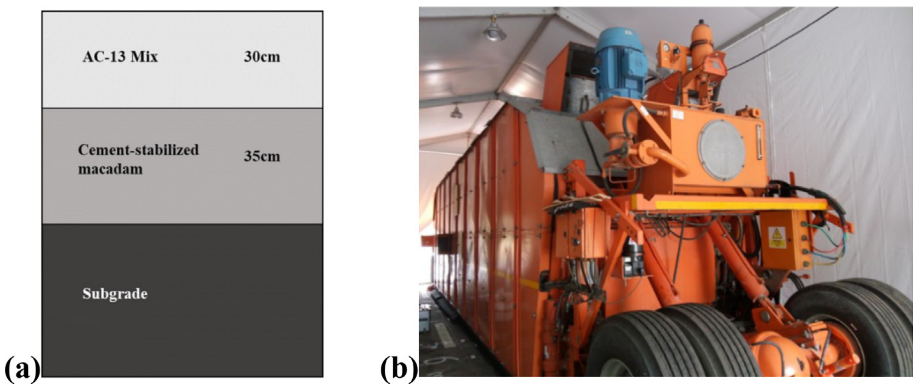

Fig. 1. Introduction of the field test. (a) Pavement structure, (b) The MLS66.

Table 1. The semi-rigid base layer was 35 cm cement-stabilized macadam. During the construction, some platinum thermistor sensors were used in the surface layer at intervals of 2 cm to record temperatures.

The mobile load simulator 66 (MLS66) which Fig. 1(b) is equipped with a single axle load with dual tires, and the magnitude of the axle load is 50kN. Its effective test length is 6.6 m. It applied for 6000 axle passes per hour and about 50,000 passes of loading are applied each day. The total loading repetitions were 0.97 million.

During the APT test, the FWD deflection and seismic modulus were measured regularly. As shown in Fig. 2, a total of five stations along the two wheel paths were tested. The distance between the adjacent station was 1 m. The FWD testing was located in section 3 to section 5 at the center of each wheel path. The loading level is 50 KN. At each test point, ten sensors were used to measure the deflections at 0, 20, 30, 45, 60, 90, 120, 150, 180, and 210 cm from the load center. So there were 3 (stations) × 11 (passes) × 2 (positions) × 3 (repetitions) = 198 deflection basins measured during the test. The deflection basins were determined by the average values of the later repetitions at each testing point. The surface temperature was recorded by the FWD equipment during the deflection measurement test.

The PSPA test was conducted on all five stations. At each station, PSPA test was carried out at four positions: two at the outer edge and the other two at the center of the wheel path. In addition, both transverse and longitudinal directions were included in the test. Moreover, the test was repeated 10 times for each direction. Therefore, there were 5 (stations) × 11 (passes) × 4 (positions) × 2 (directions) × 10 (repetitions) × 11 (sub-layers) = 48400 PSPA moduli measured during the test. Also, the temperatures were recorded by the thermistor sensors which were instrumented in the surface layer at intervals of 2 cm.

3. Backcalculation methods and the calculation of the PSPA moduli

3.1. The deflection basin regulation algorithm

The deflection basin regulation algorithm uses the inertial point and two identity points to backcalculate the moduli of the three-layer pavement structure. The detailed concepts and procedures of the algorithm have been introduced in previous research (Zhu and Sun, 2017, Zhang and Sun, 2004b)**. Also, the backcalculation accuracy of the method has been verified in these studies. The main steps of the method are shown as follows.

(1) The inertial point, one of the critical parameters in the deflection basin regulation algorithm, is firstly used to backcalculate the subgrade modulus. The inertial point has two parameters: distance from the load center (R_c) and deflection at the inertial point (D_c). It has been verified that the parameters are only related to the subgrade modulus (E_0) and the sum of surface and base thickness (H) (Sun et al., 2000). The relationship between R_c and D_c is shown in Fig. 3. $R_c = F(D_c)$ is called the inertial point parameter equation. As we can see, when the value of E_0 increases, both the values of the R_c and D_c decrease. There is only one intersection because the two curves are angled. The modulus corresponding to the inertial point is the

Table 1
The gradation of the asphalt mixture (Li et al., 2020).

Sieve size	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15
Passing rate[%]	100	98.1	82.5	56.6	29.9	19.8	13.4	9.7	6.8

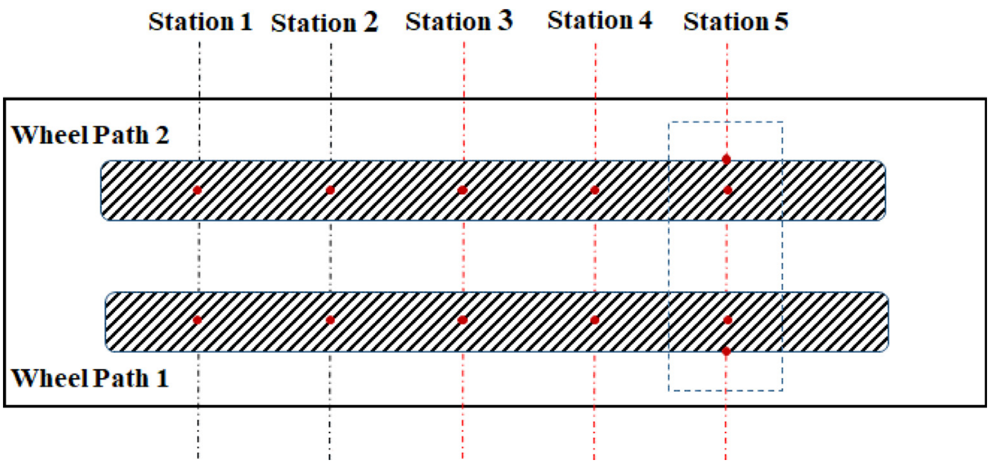

Fig. 2. The arrangement of testing points.

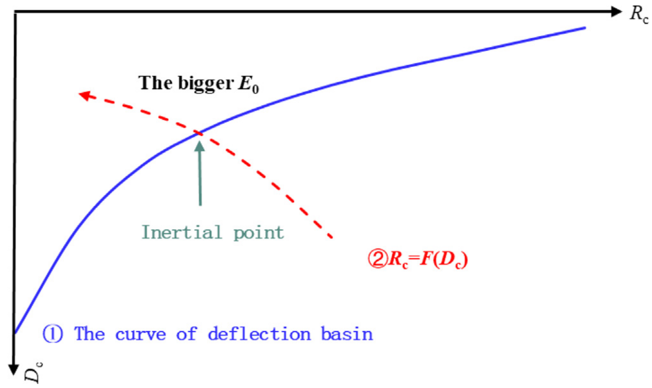

Fig. 3. Schematic diagram of the relationship between R_c and D_c.

backcalculated subgrade modulus according to the deflection basin. Therefore, the modulus of subgrade layer can be backcalculated using the following procedure.

Step 1 Determine the upper (E_{max}) and the lower (E_{min}) limit of subgrade modulus.

Step 2 Calculate the trial values of modulus (E_0' and E_0'') according to the Eqs. (1) and (2).

$$E_0' = 0.382 \times (E_{max} - E_{min}) + E_{min} \tag{1}$$

$$E_0'' = 0.618 \times (E_{max} - E_{min}) + E_{min} \tag{2}$$

Step 3 According to the value of H and the parameter equation of inertial point (Zhu et al., 2013), calculate the distance from the load center (R_c' and R_c'') and the inertial point deflections (D_c' and D_c'') corresponding to the trial values, respectively.

Step 4 Determine the measured deflections (D_m' and D_m") at R_c' and R_c" based on the measured deflection basins, and calculate the corresponding absolute values of deflection difference ($|\Delta w'|$ and $|\Delta w''|$). If $|\Delta w'|>|\Delta w''|$, then $E_{min} = E_0'$, otherwise $E_{max} = E_0''$.

Step 5 If the difference between E_{max} and E_{min} is less than the specified accuracy, then the iteration is terminated; and output the backcalculated subgrade modulus ($E_0=(E_{max} + E_{min})/2$), otherwise, return to step 2.

The inertial point parameter equation used in this paper are shown as follows:

$$R_c = (18.814 + 0.073E_0/H) \times H^{0.995} \times E_0^{-0.327} \tag{3}$$

$$D_c = (79.5 - 0.417E_0/H) \times H^{-0.987} \times E_0^{-0.676} \tag{4}$$

The reliability and accuracy of the backcalculation method based on the parameter equation was proved by the comparison with the backcalculation results based on other backcalculation methods such as MODULUS, EVERCALC and WESDEF (Zhu et al., 2013).

(2) After the subgrade modulus is confirmed, the two identity points (Ipoint1 and Ipoint2) are used to backcalculate the moduli of surface and base layer. In this article, the Ipoint1 referred to the load center while the Ipoint2 was located at 20 cm away from the load center (Zhu and Sun, 2017). The procedures for backcalculating the moduli of the surface and base layer are shown as follows.

Step 1 Determine the initial trial value of asphalt layer modulus (E_a, $E_a = (E_{a1} + E_{a2})/2$) and initial trial value of base modulus (E_b, $E_b = (E_{b1} + E_{b2})/2$) according to the range of surface modulus ($E_{a1} \sim E_{a2}$) and the range of base modulus ($E_{b1} \sim E_{b2}$).

Step 2 Adjust E_b to let the absolute value of the difference ($\left|w^t_{Ipoint1} - w^m_{Ipoint1}\right|$) between the theoretical deflection ($w^t_{Ipoint1}$) and the measured deflection ($w^m_{Ipoint1}$) at Ipoint1 be less than the specified precision ε_1; and the E_a is kept constant.

If $\left|w^t_{Ipoint1} - w^m_{Ipoint1}\right| < \varepsilon_1$, then go to step 4, otherwise, decrease the base modulus (assign E_b to E_{b2}, then $E_b=(E_{b1} + E_{b2})/2$ when $w^t_{Ipoint1} < w^m_{Ipoint1}$ and increase the base modulus (assign E_b to E_{b1}, then $E_b=(E_{b1} + E_{b2})/2$) when $w^t_{Ipoint1} > w^m_{Ipoint1}$. Repeat this step until the accuracy requirement is met.

Step 3 Verify whether the absolute value of the difference ($\left|w^t_{Ipoint2} - w^m_{Ipoint2}\right|$) between the theoretical deflection ($w^t_{Ipoint2}$) and the measured deflection ($w^m_{Ipoint2}$) at Ipoint2 is less than the specified precision ε_2.

If $\left|w^t_{Ipoint2} - w^m_{Ipoint2}\right| < \varepsilon_2$, then go to step 4, otherwise decrease the surface modulus (assign E_a to E_{a1}, then $E_a=(E_{a1} + E_{a2})/2$ when $w^t_{Ipoint2} < w^m_{Ipoint2}$ and increase the surface modulus (assign E_a to E_{a2}, then $E_a=(E_{a1} + E_{a2})/2$) when $w^t_{Ipoint2} > w^m_{Ipoint2}$ and then turn to step 2.

Step 4 Stop calculation, output E_a, E_b, and E_0.

3.2. Determination of the seismic modulus from the PSPA test

In this paper, the PSPA test was used to measure the seismic modulus of the asphalt layer at the different surface layer depths during the APT test. The PSPA device, as shown in Fig. 4, consists of a seismic wave emission source, two receivers, a data transmission system and a computer equipped with giving commands and storing signals (Zhu et al., 2013, Yang et al., 2015, Li et al., 2020, Baker et al., 1995). During the PSPA test, the emitter conducts vertical excitation on the surface and generates shear waves, compress waves and Rayleigh waves. After the wave propagating a certain distance, only the Rayleigh waves remains. Therefore, the principle of the PSPA test is that the average surface layer modulus calculated by measuring the Rayleigh wave velocity propagating between the source and the two receivers and using the Poisson's ratio of the materials. The wave velocity is confirmed by the time records from the receivers. In this paper, the seismic modulus based on the PSPA test can be calculate by the Eq. (5) (Jurado et al., 2012, Nazarian et al., 1999).

$$E = 2\rho[(1.13 - 0.16\upsilon)V_R]^2(1+\upsilon) \tag{5}$$

where E is the surface layer modulus, ρ is mass density, υ is Poisson's ratio, V_R and is the velocity of the seismic waves.

4. Results and discussion

Based on the deflection basin regulation algorithm, the layer moduli were backcalculated from the deflection basins. In the back-calculation process, the rigid layer depth was set to 550 cm in order to simplify the calculation model Table 2 shows the backcalculated results, which were the average moduli of each layer. As we can see in the table, the backcalculated subgrade modulus decreases relatively obvious at the beginning, while its variation is small during the whole loading. After the loading, the backcalculated subgrade moduli have decreased almost 16%. At the same time, the backcalculated base moduli have decreased 54.3%. The difference is that there is no obvious variation pattern of the backcalculated surface layer moduli during the loading. This may due to the backcalculated surface layer modulus is significantly affected by temperatures.

The measured seismic moduli based on the PSPA tests are listed in Table 3. To be compared with the backcalculated surface layer modulus, the measured moduli were modified to 20 ℃. The results are also in the table.

The temperature correction model used in this study is developed by Li and Nazarian (1995), and then calibrated to modify the measured seismic moduli. The temperature correction formula is shown as follows:

$$E_{20} = 1.064E_T/(1.344 - 0.014T) \tag{6}$$

Where T is the average temperature of the surface layer, the unit is ℃. E_{20} and E_T are the moduli at 20 ℃ and the measured T temperature (℃), respectively. The units of the modulus are GPa.

As we can see that, the measured seismic moduli are obviously much larger than the backcalculated surface layer moduli. The backcalculated surface layer modulus is corrected to 20 ℃ based on the following equation to better compare the measured seismic modulus (Li et al., 2020). The corrected backcalculated surface layer modulus (E_{20B}) are listed in the Table 4.

$$E_{20B} = E_{Tm} * 10^{-0.0292(T0-Tm)} \tag{7}$$

After the temperature correction, the attenuation patterns of the surface layer moduli from the FWD test and PSPA test at the same temperature are shown in Fig. 5.

It can be seen that the attenuation patterns of the surface layer modulus backcalculated from the measured deflections is consistent with those obtained from the PSPA tests. Specifically, the surface layer modulus firstly increased and then decreased with the rise of the repetitions. It may be caused by the compaction effect for the asphalt mixture by the repeated

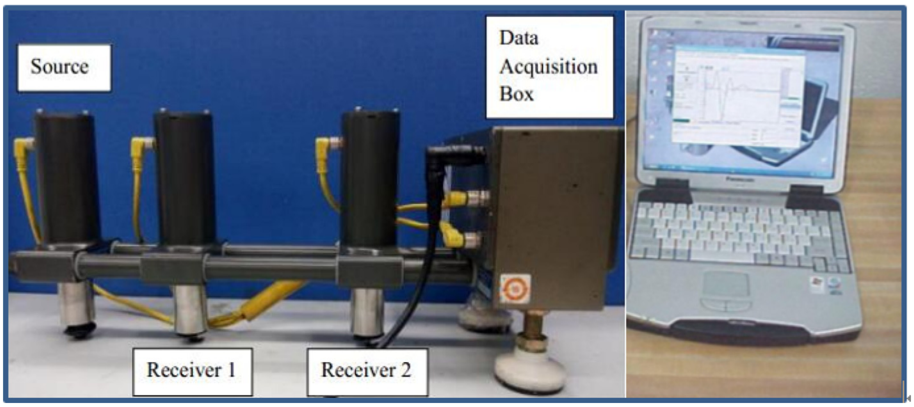

Fig. 4. Components of PSPA.

Table 2
The backcalculated moduli under different loading applications.

Loading repetitions/ 10^4	Temperature (℃)	Backcalculated asphalt moduli (MPa)	Backcalculated base moduli (MPa)	Backcalculated subgrade moduli (MPa)
0	23.8	7257	115,418	141.3
2	19.0	6501	89,375	133.8
5	19.9	7450	85,141	127.7
7.5	19.7	7446	80,364	126.4
12	18.4	7304	79,414	125.6
16	19.0	7670	71,108	124.6
73.5	20.3	7418	70,448	123.7
79.5	21.0	7665	68,880	122.4
85	22.7	8425	57,821	121.2
91	20.9	6826	54,982	119.9
97	19.9	6125	52,631	118.8

Note: The temperature is measured by the FWD equipment.

Table 3
The seismic moduli from PSPA test.

Loadingrepetitions (10^4)	Temperature(℃)	Seismic modulus(GPa)	Corrected seismic modulus (GPa)
2	20	14.33	14.33
5	21	17.10	17.33
7.5	21	18.70	18.95
12	22	19.38	19.90
16	22	19.55	20.08
73.5	21	17.36	17.59
79.5	22	17.03	17.49
85	23	16.74	17.43
91	23	16.09	16.75
97	22	16.28	16.72

Note: The temperature is measured by the thermistor sensors.

Table 4
The corrected backcalculated surface layer modulus.

LP (10^4)	0	2	5	7.5	12	16	73.5	79.5	85	91	97
CBSLM (MPa)	5621	6953	7500	7598	8134	8203	7270	7167	7026	6425	6166

Note: The LP means loading repetitions, and the CBSLM means corrected backcalculated surface layer modulus.

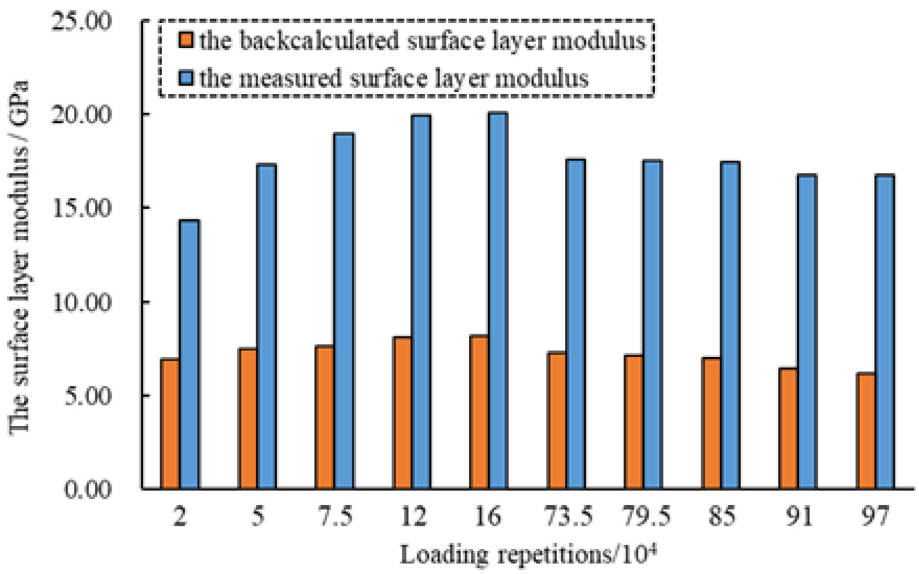

Fig. 5. The attenuation patterns of the surface layer moduli.

loadings for the increase of the surface layer modulus at the initial loading stage. The number of the loading repetitions corresponding to the bigger surface layer modulus is roughly at 160,000. However, the FWD test is not continued after 160,000 loading test due to the limitations of the testing conditions. We cannot assume that the surface layer modulus reaches its maximum value after 160,000 loading repetitions. The surface layer modulus shows a decreasing trend from 735,000 loading tests, the decrease exhibited the accumulation of the fatigue damage within the asphalt mixture caused by APT loading. The attenuation patterns of the surface layer modulus in the damage stage is described using the Eq. (8).

$$E_a = 421100 \cdot N^{-0.6119}, R^2 = 0.89 \tag{8}$$

where E_a means the backcalculated surface layer modulus, its unit is MPa; and N means the loading repetitions, the unit is thousand.

In addition, the ratio of the measured seismic modulus to the backcalculated surface layer modulus is plotted in Fig. 6. It shows that the ratio ranges between 2.06 and 2.71, implying the obvious difference between those two types of moduli. This may be because the surface layer modulus based on the PSPA measured under notably higher frequency than the FWD test.

With the rise of the loading repetitions, the variation pattern of the backcalculated base modulus is different from that of the backcalculated surface layer modulus. The attenuation pattern of the base layer modulus is shown in Fig. 7.

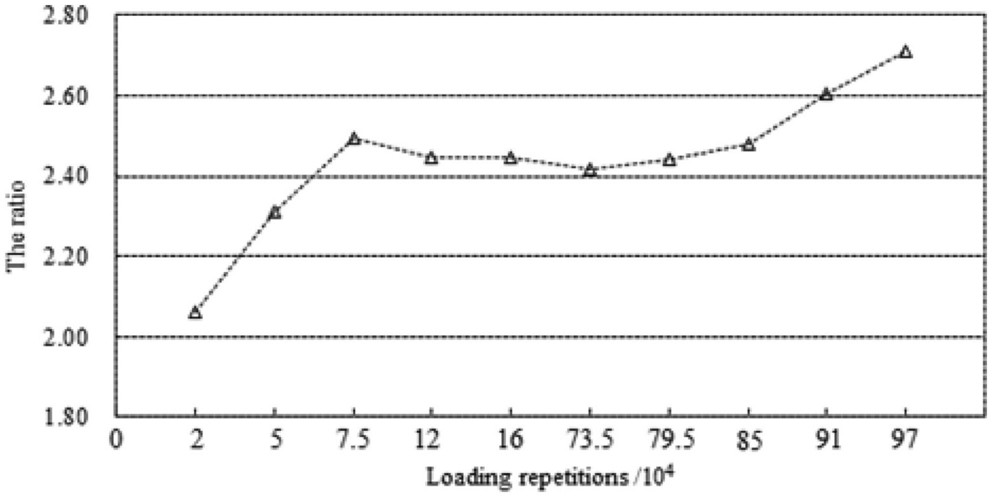

Fig. 6. The ratio between the seismic modulus and the backcalculated surface layer modulus.

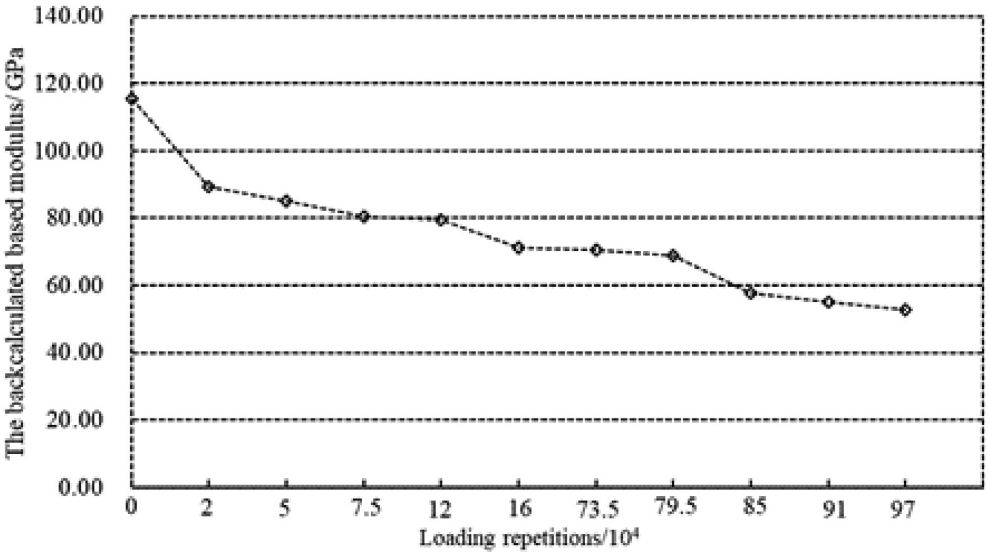

Fig. 7. The attenuation patterns of the base layer moduli.

As we can see, the backcalculated base layer modulus always declines with the increasing loading repetitions. This may because the compression has no effect on the base layer. As a result, the decrease in the backcalculated base layer modulus is mainly due to the accumulation of damage by the repeated APT loadings. The attenuation pattern of the base layer modulus in the damage stage is shown as follows:

$$E_b = 128000 \cdot N^{-0.1096}, \ R^2 = 0.83 \tag{9}$$

where E_b is the backcalculated base layer modulus, the unit is MPa.

It is worth noting that the attenuation patterns of the structural layer modulus need further verification because of the discontinuity of the measurement.

5. Conclusions

This research aimed to investigate the attenuation mode of the layer modulus of asphalt pavement in the APT test. A full-scale experimental section was constructed and tested using the APT facility. Two NDT methods, named FWD technology and PSPA test, were used to measure the layer modulus of asphalt pavement during the APT test. The variation patterns of layer moduli measured by FWD and PSPA were evaluated and compared. The main conclusions are shown as follows:

(a) The variation patterns of asphalt layer moduli backcalculated from FWD basins are consistent with those obtained from PSPA tests. The modulus of the asphalt layer increased firstly and then decreased with the rise of the loading repetitions. The modulus values of the asphalt layer measured from PSPA tests were obviously larger than those backcalculated from FWD basins. The ratio of the seismic modulus to the backcalculated surface layer modulus ranged between 2.06 and 2.71.

(b) The backcalculated base layer modulus always declines with the increasing loading repetitions, implying that the compaction effect has almost no effect on the base layer. The attenuation patterns of the modulus of the asphalt layer and base layer in the damage stage are described as $E_a = 421100 \cdot N^{-0.6119}$ and $E_b = 128000 \cdot N^{-0.1096}$, respectively.

(c) Our study was conducted indoors and the temperature was corrected to 20 ℃, only the effect of load on modulus variation was considered. So next step may be to study the variation of modulus under the coupling of load and environmental factors and to verify the attenuation pattern of the structural layer moduli.

Conflict of interest

All the authors have no conflict of interest with the funding entity and any organization mentioned in this article in the past three years that may have influenced the conduct of this research and the findings.

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