Research on Variation Law of Back-Calculation Modulus of Asphalt Pavement Layer

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Abstract. Based on in-situ FWD testing and laboratory dynamic modulus test, the influence of loading level, position and pavement temperature on FWD back calculated modulus and the relation between back calculated modulus and dynamic modulus was analysed. The structure combination of asphalt layer was determined based on pavement temperature profile and the composite modulus was calculated based on laboratory modulus test and in-situ measured pavement temperature. The results show that loading level had little influence on back calculated modulus and testing position had much more influence on back calculated modulus than loading level. The back calculated modulus and composite modulus decreased with temperature increase, when temperature was low back calculated modulus was greater than composite modulus, when temperature was in room temperature back calculated modulus was equal to composite modulus and when temperature was high back calculated modulus was less than composite modulus. For relation between back calculation modulus and temperature, temperature correction coefficient for back calculation modulus was developed and for relation between back calculation modulus and composite dynamic modulus, correction coefficient model between them was developed.

Keywords. FWD, back-calculation modulus, composite dynamic modulus, temperature correction coefficient, laboratory and in-situ modulus correction coefficient.

1. Introduction

Asphalt pavement structure is affected by many factors such as construction variation, temperature and load. Its structural modulus has great variation and changes with changes in load size, location, season, and temperature. Existing studies have shown that fatigue cracks, ruts and other damages of the pavement structure are closely related to the mechanical responses such as stress and strain. The mechanical response of the pavement structure under a certain load is mainly affected by the structural modulus [1-2]. Therefore, it is of great significance to study the change law of pavement structure modulus for understanding the behavior of asphalt pavement structure and reasonable analysis of pavement structure design.

Different from the idealization and simplification of the stress conditions and environmental conditions of the laboratory material modulus test, the acquisition of the pavement structure modulus is more complicated and needs to be tested on site. The obtained modulus can better reflect the actual...
stress state of the pavement structure. At present, the most widely used test equipment is the drop weight deflection instrument (FWD). The back calculation of the pavement structure layer modulus based on the FWD deflection basin has become a research hotspot in the highway industry, and great progress has been made [3-4]. However, the variation of inverse modulus of different pavement structures and the law of temperature change need to be studied urgently. In particular, at present, there is no temperature correction model for FWD inverse modulus in Chinese code, which makes it difficult to compare the bearing capacity of pavement at different temperatures. The relationship between the FWD inverse modulus and the test modulus of indoor test materials is also lacking research, resulting in a disconnect between the indoor modulus and the on-site modulus, which is not conducive to the analysis of the pavement structure [5].

In view of the above problems, combing the FWD test data of the permanent asphalt pavement test road, the back-calculation modulus of asphalt layer with load size, location, and temperature was analyzed. A temperature correction model based on back-calculation modulus of asphalt layer and the relationship between the back-calculated modulus of asphalt pavement layer and the indoor dynamic modulus were also established, which provide a reference for pavement structure design and analysis.

2. Research Methods

2.1. FWD Detection
The FWD test was performed at the locations where the sensors were embedded in the five structural sections of the permanent pavement test road [6-8]. The drop weight deflection instrument (FWD) uses Dynatest Model 8000. There are 9 sensors in the device, the distance from which to the center of the load is 0, 203, 305, 457, 610, 914, 1524 and 1829 mm. The FWD test uses a 30 cm diameter bearing plate, and three levels of load are used at each measurement point, which are 30 kN, 40 kN, 50 kN, that is, 424 kPa, 566 kPa, 707 kPa. Each load was repeated three times. According to the test plan, FWD testing is performed under different temperature conditions and in different seasons.

2.2. Back Calculation Model
The American EVERCALC was used for back-calculation, which is based on the elastic layered theory system. The division of the structural layer has a great impact on back calculation results, and it needs to be a reasonable combination [9]. For structure 1, structure 2, structure 3 and structure 4, the asphalt layers are thick. If the temperature gradient in the structure layer is large during the test, the modulus will be greatly different. At this time, the asphalt layer is divided into two equal layers for back calculation analysis, otherwise, the asphalt layer is combined into one layer for analysis. The criterion of the temperature gradient is that when the difference between the road surface temperature and the bottom temperature of the asphalt layer is greater than or equal to 10 °C, the asphalt layer needs to be divided into two layers for analysis, according to which, the five-structure asphalt layers were divided into one layer. In order to reduce the number of divided structural layers, Structure 4 and Structure 5 respectively combine the two improved soil layers with similar modulus into one structural layer.

2.3. Laboratory Dynamic Modulus Test and Structural Composite Modulus Calculation
In order to compare with the back-calculated on-site modulus, asphalt mixture samples of each layer were taken from the site, and the test specimens were formed in laboratory according to the field compaction degree to perform dynamic modulus tests at different temperatures and frequencies according to AASHTO TP62 [10]. Three test temperatures, 4.4 °C, 21.1 °C and 40 °C were used. At each test temperature, a 10 Hz loading frequency was used to determine the dynamic modulus.

The asphalt pavement layer is composed of different types of asphalt mixtures. The indoor dynamic modulus test obtains the modulus of a certain asphalt mixture, while the entire asphalt layer was generally treated as a whole layer when FWD back calculated, and its back calculation modulus is a composite modulus composed of different types of asphalt materials. In order to correspond to the
on-site structural modulus, a regression relationship between the dynamic modulus of each layer of asphalt mixture obtained from the indoor test and the test temperature should be established firstly, and then the intermediate temperature of each asphalt layer of the pavement structure during the FWD test should be substituted into the regression relationship to calculate the modulus of the asphalt material in the pavement structure. Finally, the composite dynamic modulus of the entire asphalt layer is obtained by analogy. The calculation principle of composite modulus of pavement structure can refer to the literature [11-12]. The intermediate temperature of each asphalt layer is determined by interpolation calculation of the temperature field of the pavement structure measured by the sensor.

\[
E_{\text{composite}} = \frac{E_1 E_2 E_3 (H_1 + H_2 + H_3)}{E_1 E_2 H_2 + E_1 E_3 H_3 + E_2 E_3 H_1}
\]

In the equation (1), \(H_1, H_2, H_3\) is the thickness of various asphalt layers; \(E_1, E_2, E_3\) is the dynamic modulus of laboratory test corresponding to the intermediate temperature of various asphalt layers.

3. Influencing Factors of Back Calculation Modulus

3.1. Influence of Load Level
From the analysis of changes in back calculation modulus at different loading levels at the same test point in the same test section, it can be found that the change in loading level had little effect on the back calculation results, and their standard deviation and coefficient of variation were small. Table 1 shows the results of the back calculation of the asphalt mixture modulus of three structures at the same measurement point in April 2007. The coefficient of variation of the back calculation results of different structures does not exceed 10%. Among them, the variation coefficients of structures 4 and 5 containing semi-rigid material layers are larger than those of flexible pavement structures 1, 2, and 3. Thanks to the little influence of the load level in the back-calculated modulus of the asphalt layer, in the actual pavement analysis, the effect of the axial load level can be considered to ignore when the back-calculation modulus value is taken.

| Structure | Back calculation modulus (MPa) | Average (MPa) | Standard deviation (MPa) | Variation coefficient (%) |
|-----------|-------------------------------|---------------|--------------------------|--------------------------|
|           | 30kN  | 40kN  | 50kN  | 30kN  | 40kN  | 50kN  | 30kN  | 40kN  | 50kN  | 30kN  | 40kN  | 50kN  | 30kN  | 40kN  | 50kN  | 30kN  | 40kN  | 50kN  | 30kN  | 40kN  | 50kN  |
| Structure 1 | 10793.0 | 10285.5 | 9874.4 | 10317.6 | 375.7 | 3.6 |
| Structure 2 | 10728.8 | 10850.2 | 10586.8 | 10721.9 | 107.6 | 1.0 |
| Structure 3 | 9123.3 | 9451.9 | 9712.7 | 9429.3 | 295 | 3.1 |
| Structure 4 | 9315.8 | 10651.3 | 10212.5 | 10059.9 | 555.8 | 5.5 |
| Structure 5 | 6358.3 | 6456.6 | 7409.8 | 6741.6 | 474.2 | 7.0 |

3.2. Position Variation Analysis
Variations in the back calculation modulus of different measurement points at the same time can reflect the variability of pavement construction, which is affected by many factors such as construction compaction, thickness, material segregation and so on. It plays an important role in studying the reliability of pavement design. The back calculation modulus variation results of different measurement points in April of the year were shown in table 2. It shows that the variation of the back calculation modulus in different measuring points is obviously different with the combination of pavement structures. The coefficients of variation of structure 1, structure 2 and structure 3 with similar pavement material combinations are small, while the coefficients of variation of structure 4 and structure 5 with semi-rigid material layers are large. The back calculation modulus of semi-rigid
materials has a large variation, which results in a large variation of the inverse calculation modulus of the asphalt layer. From the overall comparison, the back-calculated modulus variation of different measurement points is greater than that of different load levels at the same measurement point.

Table 2. Back calculation modulus variation on different spot.

| Structure | Structure 1 | Structure 2 | Structure 3 | Structure 4 | Structure 5 |
|-----------|-------------|-------------|-------------|-------------|-------------|
| Average (MPa) | 10130.4 | 9212.8 | 9218.8 | 7315.8 | 7802.0 |
| Standard deviation (MPa) | 985.4 | 871.8 | 1876.3 | 1128.8 | 3058.0 |
| Variation coefficient (%) | 9.7 | 7.2 | 10.2 | 15.4 | 39.0 |

3.3. Effect of Temperature

The deflection basin data at various typical test temperatures within the range of the pavement temperature field is selected, and the back calculation is performed according to the structural layer division of figure 1. The intermediate temperature of the asphalt layer is used as the representative temperature of the pavement structure. As can be seen from the figure 2 of the intermediate temperature of the asphalt layer, the temperature has a greater influence on the back calculation modulus of the asphalt layer. As the temperature increases, the back calculation modulus of the asphalt layer of each structure gradually decreases.

![Figure 1. Structure model of FWD back-calculation.](image)

![Figure 2. Back-calculation modulus and temperature curve for all structure section.](image)
The trend of the back calculated modulus of each structure's asphalt layer with the temperature of the pavement structure conforms to the change of the exponential function. The relationship between the back calculated modulus and temperature are analyzed by using the exponential regression. The regression relationship is shown in table 3, and the correlations are good.

**Table 3. Regression relationship between back calculated modulus and temperature.**

| Structure   | Regression relationship | Temperature correction coefficient | Correlation coefficient ($R^2$) |
|-------------|-------------------------|-----------------------------------|--------------------------------|
| Structure 1 | $E = 30829e^{-0.0709T}$ | $K = e^{-0.0709(20-T)}$           | 0.99                           |
| Structure 2 | $E = 35748e^{-0.0721T}$ | $K = e^{-0.0721(20-T)}$           | 0.99                           |
| Structure 3 | $E = 26152e^{-0.0652T}$ | $K = e^{-0.0652(20-T)}$           | 0.97                           |
| Structure 4 | $E = 40441e^{-0.0731T}$ | $K = e^{-0.0731(20-T)}$           | 0.98                           |
| Structure 5 | $E = 46785e^{-0.0791T}$ | $K = e^{-0.0791(20-T)}$           | 0.92                           |
| All structural synthesis | $E = 34309e^{-0.0708T}$ | $K = e^{-0.0708(20-T)}$           | 0.94                           |

The ratio of the modulus at the standard reference temperature to the back calculation modulus of the asphalt surface layer at any temperature was used as the temperature correction coefficient of the back calculation modulus. With 20 °C as the reference temperature, according to the regression analysis results of the modulus temperature relationship model, the temperature correction coefficients for different structures and the universal temperature correction coefficients for all structures are shown in table 3. Modification coefficient model can be used to modify the modulus at different temperatures to the reference temperature, which is helpful for the comparison of the equivalent conditions of pavement structure response and back-calculated modulus.

4. Relationship between Back-Calculated Modulus and Indoor Dynamic Modulus

4.1. Structural Composite Dynamic Modulus Calculation

The test results of the dynamic modulus of various asphalt mixture materials are shown in table 4. The relationship between the dynamic modulus of each type of material and the temperature is established by exponential regression, which is used to calculate the dynamic modulus of the asphalt layer at different temperatures in the road structure.

**Table 4. HMA dynamic modulus test results (MPa).**

| Test temperature (°C) | SMA-13 | AC-20 | AC-25 | LSPM-30 | Fatigue layer |
|-----------------------|--------|-------|-------|---------|---------------|
| 4.4                   | 16367  | 19193 | 20947 | 14336   | 16825         |
| 21.1                  | 8253   | 10615 | 10703 | 8020    | 8244          |
| 40                    | 2515   | 4106  | 3417  | 3449    | 2171          |

Because the temperature field of the asphalt pavement structure changes with temperature, the temperature at different depths in the pavement structure is different, so the composite modulus of the structure calculated from the indoor dynamic modulus cannot be calculated at the same temperature. In this paper, the temperature of the middle point of this layer was taken to represent the temperature of this layer of asphalt. Taking structure 2 as an example, the road temperature field corresponding to the typical temperature deflection basin of the structure during detection is shown in figure 3.
The intermediate temperature of each asphalt layer was calculated by interpolation, as seen in table 5. According to the table 5, the corresponding modulus of various materials from the intermediate temperature of the asphalt layer was calculated. And the structural composite modulus was calculated according to equation (1). The results are shown in table 6.

**Table 5.** Asphalt layers mid-depth temperature of section 2 (°C).

| Date       | SMA | AC-20 | AC-25 | LSPM | Fatigue layer |
|------------|-----|-------|-------|------|--------------|
| 2006-3-24  | 20.6| 18.5  | 16.8  | 14.4 | 12.7         |
| 2006-4-28  | 25.8| 22.3  | 19.5  | 18.5 | 18.0         |
| 2006-5-30  | 43.9| 39.6  | 36.1  | 31.3 | 27.9         |
| 2006-12-6  | 3.8 | 3.6   | 3.4   | 4.0  | 4.7          |
| 2007-2-11  | 9.1 | 6.5   | 4.3   | 4.4  | 4.6          |
| 2007-6-6   | 35.8| 33.3  | 31.1  | 30.6 | 30.2         |
| 2007-7-19  | 39.5| 37.6  | 36.0  | 32.9 | 30.8         |
| 2007-11-21 | 13.4| 11.1  | 9.1   | 8.6  | 8.6          |

**Table 6.** Dynamic modulus and structure composite dynamic modulus of section 2 (MPa).

| Date       | SMA    | AC-20 | AC-25 | LSPM | Fatigue layer | Composite modulus |
|------------|--------|-------|-------|------|---------------|------------------|
| 2006-3-24  | 8446.2 | 11761.6| 12999.0| 10313.7| 12192.5       | 11144.4          |
| 2006-4-28  | 6480.7 | 10082.2| 11545.3| 8854.5 | 9625.9        | 9289.8           |
| 2006-5-30  | 1779.4 | 4196.0 | 4548.9 | 5220.4 | 5628.2        | 3945.0           |
| 2006-12-6  | 16728.8| 19692.7| 21680.7| 14512.7| 16658.4       | 17550.2          |
| 2007-2-11  | 13789.2| 17983.0| 21026.0| 14349.0| 16707.9       | 16638.8          |
| 2007-6-6   | 3468.8 | 6038.7 | 6266.6 | 5388.6 | 4849.0        | 5179.6           |
| 2007-7-19  | 2625.9 | 4747.0 | 4567.8 | 4841.7 | 4651.0        | 4257.3           |
| 2007-11-21 | 11620.0| 15447.3| 17695.9| 12527.3| 14396.9       | 14265.4          |

4.2. Comparison of Back Calculated Modulus and Structural Composite Modulus
A comparison of back calculated modulus of each structure at different temperatures with the composite modulus of the corresponding pavement structure is shown in figure 4. The temperature in the graph refers to the intermediate temperature of the entire asphalt layer of the road surface. It can be seen that the back calculation modulus and structural composite modulus decrease with increasing temperature. When the temperature is low, the back calculation modulus is greater than the composite modulus. As the temperature increases, the back calculation modulus and the composite modulus coincide at room temperature. And when the temperature continues to rise, the back-calculated modulus is lower than the composite modulus at high temperature. Structures 1, 2, 3, 4, and 5 are equivalent to the composite modulus at 15.0, 19.6, 11.3, 23.7 and 22.4 °C respectively. It indicates that the back calculation modulus of the flexible pavement structure between 10 and 20 °C is equal to the
composite modulus, and that of the semi-rigid layer pavement structure between 20 and 25 °C is equivalent to the composite modulus.

In order to establish the correlation between FWD back calculation modulus and structural composite dynamic modulus, a correction factor $\lambda$ is introduced between the two. $\lambda$ is defined as the ratio of the back-calculated modulus to the composite dynamic modulus of the structure at the intermediate temperature of the same asphalt layer. It can be observed the change law with temperature in figure 5. It indicates that the back calculation modulus and the composite modulus correction factor $\lambda$ of each structure decrease with increasing temperature, and the range of the correction factor $\lambda$ equal to 1 is between 10 and 25 °C.

**Figure 4.** Comparison of back calculated modulus and composite modulus.
Figure 5. Correction coefficients between back calculated modulus and composite modulus.

The calculation relationship between the correction factor $\lambda$ and the road temperature was established according to the exponential regression model, which has a good correlation, as shown in Table 7. A more general relationship between all structural correction coefficients and temperature data was also given in the table, covering a variety of pavement structures, which can provide a reference for the conversion of back calculation modulus and composite modulus. It can be seen that the back calculation modulus and the composite dynamic modulus are closer to each other under room temperature conditions. Therefore, in the actual road surface analysis, it is recommended that the back calculated modulus be converted to the normal temperature condition by the temperature correction coefficient and then the relevant comparison be performed, so that there is comparability under the same conditions.

Table 7. Correction coefficients and temperatures regression relation.

| Structure   | Regression coefficient indoor and outdoor modulus | Correlation coefficient/$R^2$ |
|-------------|--------------------------------------------------|---------------------------------|
| Structure 1 | $\lambda = 1.4271e^{-0.0237T}$                  | 0.98                            |
| Structure 2 | $\lambda = 1.6659e^{-0.0257T}$                  | 0.95                            |
| Structure 3 | $\lambda = 1.3835e^{-0.0291T}$                  | 0.88                            |
| Structure 4 | $\lambda = 1.9233e^{-0.0288T}$                  | 0.82                            |
| Structure 5 | $\lambda = 1.8769e^{-0.028T}$                   | 0.71                            |
| All structural synthesis | $\lambda = 1.5849e^{-0.0243T}$ | 0.71                            |

5. Conclusion

(1) The back calculation modulus of the asphalt layer is less affected by the load level, and the coefficient of variation does not exceed 10%; the variation of the back calculation modulus in different measurement points of the same structure is greater than the variation of the back calculation modulus of different load levels at the same measurement point; The position of the back-calculated modulus is significantly different depending on the structure combination. The variation of the back-calculated modulus of the asphalt pavement with a semi-rigid material layer is greater than that of the flexible pavement.

(2) The back calculation modulus of the asphalt layer decreases with the increase of the pavement temperature. For different typical structures, the relationship between the asphalt layer and the temperature is established as $E = 34309e^{-0.0708T}$, and when the back calculation modulus is converted to room temperature 20 °C, the temperature correction coefficient relationship is established as $K = e^{-0.0708}$ (20-T).

(3) Both the back calculated modulus and the structural composite modulus decrease with
increasing temperature. When the temperature is low, the back calculated modulus is greater than the compound modulus. As the temperature increases, the back calculated modulus and the compound modulus coincide at normal temperature. When the temperature continues to rise, the back-calculated modulus is lower than the compound modulus at high temperature.

(4) Both the back calculation modulus and the composite modulus correction factor decrease as the temperature increases, and the range of the correction factor $\lambda$ equal to 1 is between 10 and 25 °C. For the relationship between back calculation modulus and indoor dynamic composite modulus, a calculation model is established as $\lambda = 1.5849e^{-0.0243T}$ to reflect the influence of temperature on correction factor $\lambda$, which provides a basis for the conversion of the FWD back calculation modulus and the indoor dynamic modulus.

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