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Research Article

Modulus Inversion Layer by Layer of Different Asphalt Pavement Structures

Mingming Cao ,[1] Wanqing Huang,[1] Yiwen Zou,[2] and Guomin Liu[3]

[1]*Sichuan Communication Surveying and Design Institute CO., LTD, Chengdu 61004l, China*
[2]*School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China*
[3]*School of Civil Engineering, Sichuan Vocational and Technical College of Communications, Chengdu 611130, China*

Correspondence should be addressed to Mingming Cao; 707360021@qq.com

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In order to improve the accuracy of modulus inversion of the pavement structure layer, a layer-by-layer inversion method was proposed to be compared with the traditional inversion method by inverting the modulus of each structural layer of the inverted asphalt pavement and semirigid asphalt pavement. The results show that the influence of cushion modulus on the modulus of inverted subgrade and modulus of cement-stabilized crushed stone is restricted by the cushion modulus and pavement structure characteristics, and the thicker cement-stabilized crushed stone layer is beneficial for improving inverted modulus of subgrade; besides, for the inverted asphalt pavement, the modulus of the graded crushed stone transition layer has a significant influence on the modulus inversion of cement-stabilized crushed stone. The modulus of the graded gravel transition layer inverted by these two methods is underestimated, the modulus of cement-stabilized gravel is overestimated using the traditional inversion method, and the inversion result of the inverted asphalt pavement is more significantly affected by the inversion method than the semirigid base asphalt pavement. Moreover, the modulus of the pavement structural layer is determined by the material and structural characteristics, and its recommended empirical value or the value in the indoor test does not conform to the actual value of the site; by contrast, the inversion modulus obtained using the layer-by-layer inversion method is closer to the actual value, which can be used in the design of similar pavement structures to accumulate data for determining the material modulus or the pavement structure adjustment coefficient in the pavement structure.

1. Introduction

The deflection basin can comprehensively reflect the structural characteristics (thickness, layer position), material characteristics (modulus, etc.) of each structural layer of the pavement, and external factors (temperature, humidity, and traffic conditions), and it can also indirectly evaluate the operation duration of the road, etc. [1–3]. Research on the modulus inversion of pavement structure layer mainly focuses on the following aspects: (1) the influence of the thickness of pavement structure layer, interlayer contact, and the temperature on the inverted modulus [4–7]; (2) the establishment of the correction coefficient between the modulus of each pavement structure layer material in indoor test and the inverted modulus to characterize the relationship between the inverted modulus and the actual modulus of the pavement structure [8–10]; besides, the research subject mainly includes semirigid base asphalt pavement and flexible base asphalt pavement, but inverted structure asphalt pavement is few studied.

The traditional inversion method is to substitute the initial value directly, maximum value, and minimum value of the modulus of each structural layer into the inversion software, in which the deflection value is the dynamic deflection of the pavement surface. It has been found that using the dynamic deflection makes the deviation coefficient of the inverted modulus large, especially for the base layer and the subbase layer, their deviation coefficient is mostly between 60 and 90%, and the system error of 1%~2% of the deflection sensor may lead to 10%~20% inversion modulus error

[11, 12]. In addition, so far, FWD is mostly used to test deflection basins of the pavement surface to evaluate the bearing characteristics, during which 95% of FWD load acts on the pavement surface and spreads to the underlying structural layer, and 5% is directly loaded on the roadbed. There are few studies on testing the distribution of deflection basins in each layer and inverting the modulus of each structural layer [13, 14].

RN Stubstad [15] emphasized the feasibility of controlling the quality of applying FWD to the pavement construction; the dynamic deflection value of the main layers was tested layer by layer, and the equivalent pavement modulus was solved using the empirical formula, but the evaluation of the modulus inversion of each layer was not carried out layer by layer. Based on the Wisdom Road project in Virginia, Nassar et al. [16] used FWD to test the dynamic deflection of each layer during the construction of flexible pavement to invert the modulus of the main structural layers, and the modulus of each structural layer was inverted layer by layer. Solanki et al. [17] analyzed the difference between the inverted modulus of subgrade and base layer and the laboratory test value when the FWD was loaded at different layers of the flexible pavement, but the difference in the inverted modulus under the different working conditions and using the traditional inversion method was not analyzed. Liao et al. [18] adopted the Beckman beam method to test the static deflection of semirigid pavement layer by layer and used the elastic layered system to inverse the modulus of the cement-stabilized gravel base and asphalt surface. However, because the Beckman beam method is a static test method, the test error is relatively large.

In the inverted asphalt pavement, there is a graded gravel transition layer with relatively low strength between the cement-stabilized crushed stone base and the asphalt layer, which makes the pavement structure more complex and the inverted modulus more variable. In addition, because the asphalt surface is greatly influenced by the temperature and exhibits obvious viscoelastic properties, the accuracy of the modulus inversion results of the lower layers is significantly affected, which can be improved using the layer-by-layer inversion modulus method. In this paper, a layer-by-layer inversion modulus method was proposed. Furtherly, based on the dynamic response test section of the asphalt pavement of Sichuan-Guangzhou Expressway, the inverted modulus of the three structures using the traditional inversion method and the layer-by-layer inversion method was compared.

2. Test Scheme and Inversion Method

2.1. Test Scheme. The Sichuan Sui-Guang Expressway adopts the S1 structure, four lanes in two directions; the total length of the test roadway is 646.8 m, including three types of pavement structures, as shown in Table 1. Among them, S1 (semirigid structure) is 99 m in length, S2 (inverted structure 1) is 301 m in length, S3 (inverted structure 2) is 246.8 m in length, and the total thickness is 89 cm. By referring to "Highway Subgrade and Pavement Field Test Regulations" (JTGE60-2008), the resilient modulus of the subgrade and cushion layer was tested through the load-bearing board test (Figure 1), and the PRIMAX1500 FWD was used to test the dynamic deflection of each layer from the base layer to the top of the upper layer (Figure 2), in which the sensor was installed 0 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 90 cm, 120 cm, 150 cm, 180 cm, and 210 cm away from the loading center, respectively. In addition, the FWD test of the cement-stabilized crushed stone base layer is 30 days after its construction completed, and the subsequent test intervals of each layer are within 48 h.

2.2. Layer-by-Layer Inversion Modulus Method. The layer-by-layer inversion modulus method is to firstly load FWD to the top surface of the base course to test deflection value and to determine the inverted modulus of the cement-stabilized crushed stone layer, subgrade, and cushion layer. Then, while inversing the modulus of the transition layer, the material parameters (including the conditions of fixed modulus of part of the structural layer and limiting the initial value and maximum and minimum modulus of all structural layers) were substituted in the inversion; finally, the inverted modulus of the structural layer was comprehensively determined based on multiple inversion result. The modulus of the asphalt surface layer can also be determined following the procedure above. During the inversion, the deflection value of each structural layer was adopted, and the modulus of each structural layer needs to be determined through multiple inversions layer by layer. If it is necessary, field test methods such as load-bearing plates can be used to determine the modulus of part of layers. This method reduces the number of variables of the inverted structural layer, improving the inversion accuracy, and the layer-by-layer deflection test reduces the influence of the test error.

Based on the iterative method, to invert the pavement structure layer modulus is relatively mature [19], and Mao's [20] study shows that the modulus of the linear and nonlinear inversion of the graveled pavement is relatively consistent, and the graded gravel layer can be considered a linear elastic material for inversion. Smith et al. [21] compare the existing inversion methods and believe that the dynamic inversion method is not perfect enough and the time and frequency dominated inversion methods have certain drawbacks. Therefore, this paper uses an ECERCALC5.0 program to invert the pavement structure layer modulus.

3. Modulus Inversion of Each Structure Layer of the Pavement

3.1. The Measurement of the Modulus of Graded Gravel and Subgrade Using the Load-Bearing Plate Method. The load-bearing plate method is mainly used to test the modulus of graded crushed rock and subgrade for comparison with the inverted modulus and is also used to determine the modulus of the graded crushed rock cushion layer indirectly. The test results of the resilient modulus of graded gravel and subgrade are shown in Table 2. The tested average modulus of

Table 1: The structure of the test section.

Pavement structure		S1 (semirigid structure)	S2 (inverted structure 1)	S3 (inverted structure 2)
The asphalt mastic macadam SMA upper surface layer (cm)		4		
The SBS modified asphalt AC-20°C middle surface layer (cm)		6		
The lower surface layer	The type	Asphalt AC-20°C	The SBS modified asphalt AC-20°C	ATB-25
	The thickness (cm)	8	8	12
The graded crushed stone transition layer (cm)		—	12	
The cement-stabilized crushed stone base (cm)		28	20	
The cement-stabilized crushed stone subbase (cm)		28	24	20
The graded crushed stone cushion layer (cm)		15	15	15
The total pavement thickness (cm)		89	89	89

Figure 1: Field test of the bearing plate.

Figure 2: FWD field testing.

the cushion layer by the bearing plate method is 309 MPa, and the average subgrade modulus is 161 MPa.

3.2. Influence of Modulus of the Graded Gravel Cushion Layer on the Inverted Modulus of Subgrade and Cement-Stabilized Gravel. The inversion accuracy of the modulus of each structural layer using the iteration method tends to decrease with the increase of the number of structural layers, and the optimal number is 3~4. For the subgrade and graded crushed stone cushion layer, they can be regarded as two layers for inversion when FWD is loaded on the top surface of the base course, and they must be treated as one layer when the top surface of other structural layers is loaded. But when they are regarded as two layers of inversion, and the maximum value of modulus of the graded crushed stone cushion layer is not limited, the inverted modulus value is 2271 MPa, which exceeds the upper limit of 700 MPa recommended by "Asphalt Pavement Design Specification JTG050-017." Therefore, it is necessary to study the influence of the modulus of graded crushed stone cushion layer on the inversion results of subgrade modulus and cement-stabilized crushed stone modulus. The following conclusions can be drawn from Figure 3:

(1) The inverted modulus of subgrade and cement-stabilized crushed stone both decrease with the increase of set modulus of the stone cushion layer from 100 MPa to 800 MPa, but the decreasing amplitude of the inverted modulus of subgrade, from large to small, is semirigid structure (38.44%), inverted structure 1 (23.43%), and inverted structure 2 (19.98%), while the decreasing amplitude of inverted modulus of cement-stabilized crushed, from small to large, is semirigid structure (8.11%), inverted structure 1 (20.69%), and inverted structure 2 (37.39%).

(2) As the modulus of the graded crushed stone cushion layer increases, the modulus curve of the subgrade shows two different stages, and two inflection points appear when the cushion modulus is 200 MPa (semirigid structure) and 150 MPa (inverted structure). Except for the inverted structure 2, the modulus curve of cement-stabilized crushed stone decreases linearly with the increase of the modulus of the graded crushed stone cushion layer; the modulus curve of cement-stabilized crushed stone of the inverted structure 2 shows two different stages, and the inflection point appears when the cushion modulus is 300 MPa. Smaller modulus of the graded

Table 2: Test modulus of the subgrade and graded gravel.

Structural layer	Modulus (MPa)							Average value (MPa)	Standard deviation	Variation coefficient (%)
Subgrade	97	175	220	166	192	132	144	161	37.5	23.3
Cushion layer	400	217	301	385	266	284	—	309	64.6	20.9

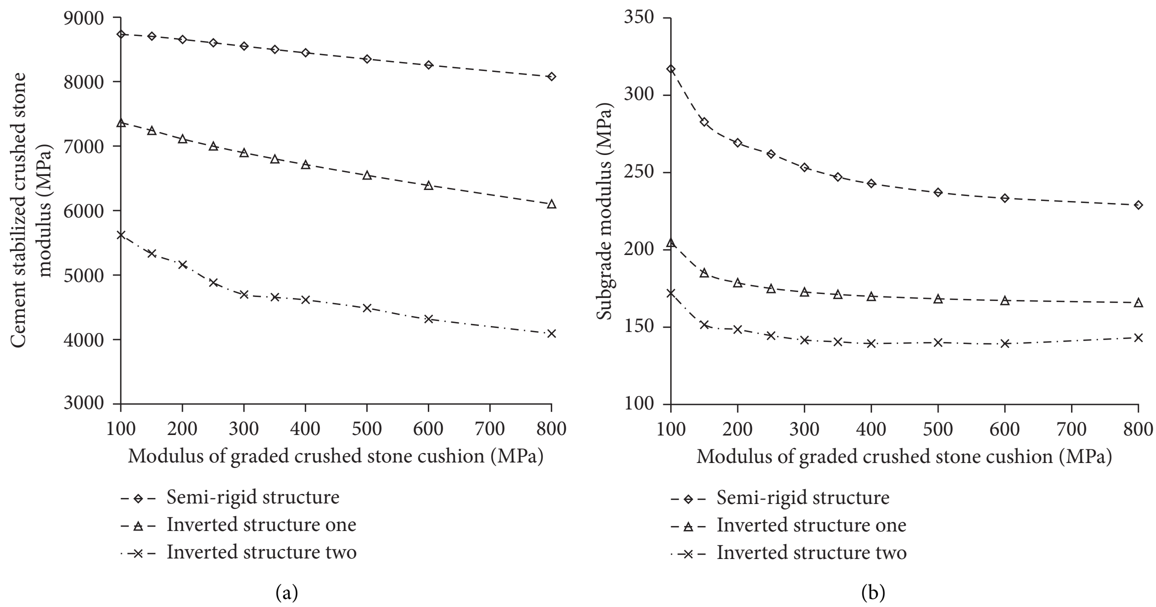

Figure 3: Influence of the variation of cushion modulus on modulus inversion of the structure layer.

crushed stone cushion layer has a greater impact on subgrade modulus and cement-stabilized crushed stone modulus, and the influence degree has a certain dependence on the pavement structure characteristics.

(3) Although the tested resilient modulus of the structure layer using the bearing plate method is the static elastic modulus, and the inverted modulus using the deflection value tested by FWD is the dynamic value, they show a high correlation [22–24]; besides, the inverted modulus of graded crushed stone cushion layer is much greater than the measured value.

3.3. Modulus Inversion of Subgrade. Based on the test of the subgrade modulus using the bearing plate, the FWD load was applied to the top surface of each structural layer to test the dynamic deflection to inverse their modulus, as shown in Tables 3 and 4.

(1) The inverted modulus of different pavement structures with different thicknesses of the cement-stabilized crushed stone layer is different; this is because when the FWD load is applied to the top surface of the base course, the inverted modulus of the thicker cement-stabilized crushed stone layer is relatively large. At the same time, in the pavement structure system, the subgrade is considered to extend infinitely in the depth direction, the equivalent modulus of the subgrade and the cushion layer is mainly dominated by the subgrade modulus, and the ratio of the cushion modulus to the subgrade modulus is much smaller than the base modulus and cushion modulus. Moreover, by regarding the subgrade and cushion layer as two layers and one layer, the inverted modulus of the cement-stabilized gravel layer is 6881 MPa and 6330 MPa, respectively, indicating that combining them as one layer has little effect on the inversion value of the modulus of the cement-stabilized crushed stone layer.

(2) When the FWD load is applied to the top surface of the underlying layer of three different structures, the difference in inverted equivalent modulus of the cushion top surface is the largest, in which the equivalent modulus of the cushion top surface of the semirigid structure is the largest, and that of the inverted structure 2 is the smallest. At the same time, when the FWD is loaded at different structural levels, the variation coefficient of the equivalent modulus of the top surface of the cushion layer, from larger to small, is semirigid structure (53.18%), inverted structure 1 (34.35%), and inverted structure 2 (27.28%). This is mainly because the performance of the asphalt mixture is relatively sensitive to temperature, showing obvious characteristics of viscoelastic and delayed elastic recovery [25, 26], and the deflection and the inverted modulus value are both affected by the test temperature. Besides, differences in the thickness of the underlying layer or asphalt type

Table 3: The inverted modulus of the structural layer (FWD on the top surface of the base course) (MPa).

Structure type	4-layer system	3-layer system	3-layer system	4-layer system
Semirigid structure	190	220	202	201
Inverted structure 1	166	167	172	172
Inverted structure 2	144	144	141	140
Note	Base course, subbase course, cushion layer, and subgrade	Cement-stabilized crushed stone layer, cushion layer, and subgrade	Cement-stabilized crushed stone layer, cushion layer with a modulus of 309 MPa, and subgrade	Base course, subbase course, cushion layer with the modulus of 309 MPa, and subgrade

Table 4: Inverted equivalent modulus of the top surface of the cushion layer.

Pavement structure	Layer subjected to FWD						Note
	Base course	Transition layer	Underlying layer	Middle surface layer	Upper surface layer	Average value	
Semirigid structure	243	—	502	189	191	281	Cement-stabilized crushed stone layer, asphalt surface layer, and subgrade were, respectively, combined with the cushion layer to perform inversion
Inverted structure 1	206	127	314	165	204	203	
Inverted structure 2	174	93	108	121	168	133	
Average value	207	110	308	159	188	194	

between different pavement structures induce the inversion error. At the same time, as the number of inversion variables increases, the inversion accuracy decreases, and a thicker asphalt layer can reduce its influence on the load transfer. Using the deflection of the top surface of the base course to inverse the modulus is beneficial for improving the inversion accuracy of the equivalent modulus of the top surface of the cushion layer. Therefore, the layer-by-layer inversion method is recommended to determine the modulus of each structural layer.

(3) The subgrade of the field test section is constructed continuously, and the material difference is small. The subgrade modulus under each structural layer should be the same, and when the FWD load is applied to the top surface of the base course, the average value of the inverted subgrade modulus of three sections is 172 MPa, which is 1.07 times that of the test result using the bearing plate. Therefore, the modulus of subgrade and the graded crushed stone transition layer of this section are taken the test value of the bearing plate, and the equivalent modulus of the cushion top surface is calculated to be 204 MPa, which is basically the same as the inverted equivalent modulus of the top surface of cushion layer 207 MPa. It is furtherly proving the reasonability of combining the subgrade and cushion layer into one layer.

3.4. Determination of Inverted Modulus of the Graded Crushed Stone Transition Layer. The graded crushed stone is a nonlinear granular, and its modulus is greatly affected by the stiffness of the underlying layer, so the bearing plate method cannot truly reflect the modulus of graded crushed stone transition layer of the loaded asphalt pavement, and the variability of the modulus of the graded crushed stone is large [27, 28]. It can be seen from Figure 4 that as the modulus of the graded crushed stone transition layer increases, the equivalent modulus of the top surface of the cushion layer of inverted structure changes less, while the inverted modulus of the asphalt surface layer and cement-stabilized crushed stone gradually decrease using the traditional inversion method, and the decreased amplitude of modulus of the asphalt surface layer is less than that of the cement-stabilized crushed stone layer; their decreased amplitude of modulus shows flexion points at 200–300 MPa and 300–500 MPa, respectively.

According to Table 5, it can be known that when the FWD is loaded on the top surface of the graded crushed stone transition layer, the average value of the inverted modulus of the graded gravel transition layer in three test sections is 243 MPa, which is lower than the value tested by the bearing plate. Because the graded crushed stone is a kind of nonlinear and discrete material, its strength is highly dependent on stress; when the underlying layer is a semirigid material, the modulus of the graded crushed stone transition layer (the modulus of the graded crushed stone transition

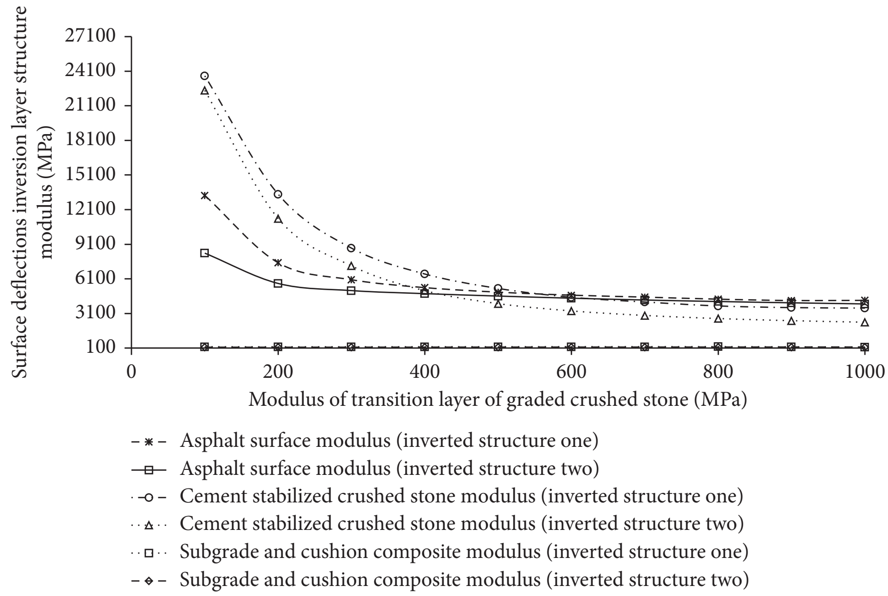

Figure 4: Influence of modulus of the graded crushed stone transition layer on modulus inversion of each structure layer.

Table 5: The inverted modulus of the graded crushed stone transition layer (MPa).

Pavement structure	Layer subjected to FWD				Note
	Transition layer	Underlying layer	Middle surface layer	Upper surface layer	
Inverted structure 1	265	150	103	163	Cement-stabilized crushed stone layer, asphalt surface layer, and subgrade were, respectively, combined with the cushion layer to perform inversion
Inverted structure 2	220	100	100	114	
Average value	243	125	102	139	

layer tested by the load-bearing board is often above 400 MPa) is greater than that when the underlying layer is subgrade. Before laying the lower asphalt layer, the inverted modulus of the graded crushed stone transition layer is greater than that based on the tested deflection by applying FWD on the top surface of the asphalt layer; this is mainly because the strength of the graded crushed stone transition layer depends on the stress. When the FWD is loaded on the top surface of the asphalt layer, the stress level of the graded crushed stone layer is lower, inducing the lower modulus. The inverted modulus of graded crushed rock by the traditional inversion method is often lower than the actual value. For the inverted asphalt pavement, the modulus of the graded crushed stone transition layer inverted by the traditional inversion method is often lower than the actual value, while the modulus tested by the bearing plate method is often higher than the actual value. Therefore, the dynamic deflection tested by applying the FWD on the top surface of the graded crushed stone transition layer is used to invert its modulus.

3.5. Modulus Inversion of the Cement-Stabilized Crushed Stone Layer. The accuracy of the inverted modulus of the inverted pavement using the EVERCALC software is lower than that of the flexible pavement. When the FWD is loaded on the asphalt pavement, the accuracy of the inverted modulus of the cement-stabilized crushed stone is less than that when the FWD is directly loaded on the top surface of the base course. According to Table 6, the following can be known:

(1) Under the condition of the same thickness of cement-stabilized crushed stone and pavement structure composition, with the increase of the thickness of the asphalt layer, the inverted modulus of cement-stabilized crushed stone gradually increases, and the inverted modulus of the base course based on the dynamic deflection of the pavement surface is the largest. Besides, the modulus of cement-stabilized crushed stone also has a certain relationship with its thickness.

(2) The modulus of the graded crushed stone transition layer has a great influence on the modulus inversion of cement-stabilized crushed stone. When the modulus of the graded crushed stone transition layer is 400 MPa, the inverted modulus of the cement-stabilized crushed stone is 0.55~0.97 times that of 243 MPa. Moreover, the closer the loading position is to the graded crushed stone transition layer, the smaller the effect of the modulus of the graded crushed stone transition layer on the modulus of the

Table 6: The inverted modulus of cement-stabilized crushed stone (MPa).

Pavement structure	The modulus of the transition layer	Layer subjected to FWD				
		Base course	Transition layer	Underlying layer	Middle surfacelayer	Upper surface layer
Semirigid structure	—	8417	—	4779	6732	11468
Inverted structure 1	Inverted value	6330	7104	2846	8490	17715
	243 MPa	—	7188	1725	3113	10980
	400 MPa	—	6725	1600	2027	6518
Inverted structure 2	Inverted value	4762	5187	7299	8707	21773
	243 MPa	—	5076	2376	2690	9116
	400 MPa	—	4903	1744	1768	5070

cement-stabilized crushed stone layer is. At the same time, the greater the modulus of the graded crushed stone transition layer, the smaller the inverted modulus of cement-stabilized crushed stone.

(3) The graded crushed stone is a kind of nonlinear and discrete material, and its modulus is greatly affected by external factors such as load and humidity. In order to accurately invert the modulus of cement-stabilized crushed stone, the FWD is recommended to load on the top surface of the base course to test deflection, so as to reduce the influence of other structural layers on the inversion results. According to different structures, different moduli of cement-stabilized crushed stone of the semirigid structure, the inverted structure 1, and the inverted structure 2 are selected as 8417 MPa, 6330 MPa, and 4762 MPa, respectively.

3.6. Modulus Inversion of the Asphalt Surface. Because the modulus of the asphalt surface is greatly affected by temperature, the inversion result needs to be corrected based on the reference temperature of 20°C. It can be known from Table 7 that the inverted modulus of asphalt surface is affected by asphalt mixture type, the thickness of asphalt surface, and the modulus of the graded crushed stone transition layer; the greater the modulus of the graded crushed stone transition layer, the lower the inverted modulus of the asphalt surface layer, but the dispersion of the inverted modulus will be greater. But, the influence of asphalt mixture type and the thickness of the asphalt surface layer is not obvious. On the whole, the thicker asphalt mixture has less influence on the modulus inversion of the asphalt surface, so the equivalent modulus of the asphalt mixture is selected based on the deflection of the pavement surface. Besides, under different inversion conditions, the inverted modulus of the asphalt surface is quite different, but its result using the traditional inversion method is closer to that using the layer-by-layer inversion method. Therefore, under different inversion criteria, the inverted modulus of the asphalt surface layer is more discrete, and it is necessary to test the deflection layer by layer to reduce the influence of the material and structural characteristics of each layer above on the inverted modulus of the structural layer.

4. The Determination of Modulus of the Structural Layer in the Test Section

As a kind of discrete material, the strength of the graded crushed stone is greatly affected by the load level and shows obvious nonlinearity, which makes its modulus value often underestimated during inversion, and the cement-stabilized crushed stone layer causes the most significant error during the modulus inversion of the inverted structure. At the same time, the modulus of subgrade and the graded crushed stone cushion layer is greatly affected by seasons and rainfall, so they are not fixed during the layer-by-layer inversion. The comparison between the inverted modulus using the layer-by-layer inversion method and the traditional inversion method is shown in Table 8.

(1) The difference in the inverted equivalent modulus of the top surface of the cushion layer using these two methods is relatively small, and the result of the layer-by-layer inversion method is 1.01~1.23 times that of the traditional inversion method. This is corresponding to the conclusions through numerical analysis in the literature [29].

(2) Because the graded crushed stone material has obvious nonlinearity, when it is in different layers, its modulus varies greatly, and it is related to the strength of the pavement structure and adjacent layers. Both inversion methods underestimate the modulus of the graded crushed rock transition layer, and the modulus of the graded crushed rock transition layer determined by the layer-by-layer inversion method is 1.4 to 2.2 times that of the traditional inversion method; besides, the thinner the cement-stabilized crushed stone layer, the greater the difference in the modulus determined by these two methods. This is because the modulus of graded crushed stone has obvious load dependence, and when the FWD is transferred to the graded crushed stone structure layer, it is already smaller than the value loaded on the top surface of this layer. Leading to a small inverted modulus, however, when the FWD is directly loaded on the top surface of the graded crushed stone structure layer, the load is greater than that on the pavement surface, and because the asphalt surface layer is not paved, the bearing plate area

Table 7: Inverted modulus of the asphalt surface (MPa).

Pavement structure	The modulus of the base course	The modulus of the transition layer	Layer subjected to FWD		
			Underlying layer	Middle surface layer	Upper surface layer
Semirigid structure	The determination of modulus inversion		5852	4634	12054
	Modulus of base course 8417 MPa		2043	3418	16626
Inverted structure 1	The determination of modulus inversion		10413	6884	11514
	The determination of modulus inversion	The modulus of the transition layer 243 MPa	7576	4444	8823
		The modulus of the transition layer 400 MPa	3598	3585	7045
	Modulus of base course 6330 MPa	The determination of modulus inversion	10847	6535	9072
		The modulus of the transition layer 243 MPa	5025	3077	12216
		The modulus of the transition layer 400 MPa	1494	1606	7454
Inverted structure 2	The determination of modulus inversion		6703	7349	9831
	The determination of modulus inversion	The modulus of the transition layer 243 MPa	4627	5927	7065
		The modulus of the transition layer 400 MPa	3477	4898	6359
	Modulus of base course 4762 MPa	The determination of modulus inversion	6396	7006	7257
		The modulus of the transition layer 243 MPa	3005	4144	9257
		The modulus of the transition layer 400 MPa	1651	2556	6073

Table 8: The comparison between the inverted modulus using the layer-by-layer inversion method and traditional inversion method (MPa).

Structure layer	Inversion calculated layer	Modulus using the layer-by-layer inversion method	Modulus using the traditional inversion method
Semirigid structure	Asphalt surface	16626	12054
	Cement-stabilized crushed stone layer	8417	11468
	Equivalent modulus of the top surface of the cushion layer	207	191
Inverted structure 1	Asphalt surface	12216	11514
	Graded crushed stone transition layer	243	163
	Cement-stabilized crushed stone layer	6330	17715
	Equivalent modulus of the top surface of the cushion layer	207	204
Inverted structure 2	Asphalt surface	9257	9831
	Graded crushed stone transition layer	243	114
	Cement-stabilized crushed stone layer	4762	21773
	Equivalent modulus of the top surface of the cushion layer	207	168

is small, the surrounding top surface is in an unconstrained state, and the 3d stress state cannot be formed inside the graded crushed stone, which makes the measured modulus is still smaller than the actual value but slightly larger than the inverted modulus using the traditional inversion method.

(3) For the semirigid structure and the inverted structure, their moduli of the cement-stabilized crushed stone are both overestimated by the traditional inversion method; but for the inverted structure, the modulus of cement-stabilized crushed stone determined by the layer-by-layer inversion method is 0.2~0.4 times that of the traditional inversion method, and for the semirigid asphalt pavement, the modulus of cement-stabilized gravel determined by the layer-by-layer inversion method is 0.74 times that of the traditional inversion method. The inverted modulus of cement-stabilized crushed stone has a certain correlation with its thickness and modulus of the adjacent layer. In the inverted asphalt pavement, the graded crushed stone

structure layer above the cement-stabilized crushed stone layer greatly weakens the bearing capacity of the cement-stabilized crushed stone layer, making the inverted modulus value much smaller than the material's actual value. Therefore, inverted asphalt pavement should adopt the layer-by-layer inversion modulus method to determine the modulus of each structural layer.

(4) While using the layer-by-layer inversion method and traditional inversion method to determine the modulus of cement-stabilized crushed stone, FWD is, respectively, loaded on the top surface of the base course and the pavement surface, the shape, and amplitude of the load distribution on the top surface of the cement-stabilized crushed stone layer are quite different, in which, with the traditional inversion method, the load transferred to the top surface of the cement-stabilized layer is in the shape of a bell with high in the middle and low on both sides, and the spreading ability to the surroundings is worse than the uniform distribution. Besides, the longer the load transfer path, the more the upper layer of the cement-stabilized gravel layer, and the more complicated the material properties, the greater the degree of overestimation of the inverted modulus [29] Because the thickness of the asphalt layer on the top surface of the inverted structure 2 is large, and the thickness of the cement-stabilized crushed stone layer is small, the modulus of the cement-stabilized crushed stone inverted by the traditional inversion method will be higher than the layer-by-layer inversion method. At the same time, the traditional inversion method underestimates the modulus of the graded crushed stone transition layer, and under certain conditions of the pavement deflection, the inverted modulus of cement-stabilized crushed stone is overestimated, and the degree of overestimation is related to the degree of underestimation of the modulus of the graded gravel transition layer. Therefore, for the inverted asphalt pavement, the modulus value obtained by the traditional inversion method is much higher than that obtained by the layer-by-layer inversion method.

In summary, while using the deflection tested by FWD to invert the modulus of asphalt pavement, the layer-by-layer inversion method is recommended; if the conditions are limited, for the inverted asphalt pavement, at least the deflection of the pavement surface, the top surface of the graded crushed stone transition layer, and the top surface of the base course need to be tested.

5. Conclusions

The modulus of the structural layer is determined by the characteristics of structure and material. The modulus tested by the indoor experiment cannot represent the modulus of the structural field layer. In the inverted asphalt pavement, there is a graded gravel transition layer of the granular body with relatively low strength and nonlinearity. For the modulus inversion of the inverted asphalt pavement, the point is the determination of the modulus of the graded crushed stone transition layer and the cement-stabilized crushed stone layer. While using the traditional inversion method, the structure and material properties of the upper layer will influence the inversion accuracy of the modulus of the underlying structure layer. The layer-by-layer inversion method is better than the traditional inversion method, especially for the inverted asphalt pavement structure.

According to the "Asphalt Pavement Design Specification JTG050-017," during the design of pavement structure, structural adjustment coefficients are introduced in the determination of material parameters of base course; however, the modulus and adjustment coefficients in the mechanical empirical method are obtained based on statistical data analysis, and their adaptability is doubtable when the test condition and environment change. By contrast, the accuracy of determining the modulus of each structural layer through the layer-by-layer inversion method is better than that of the traditional inversion method, which can effectively determine the modulus of each layer and structural adjustment coefficients, providing a basis for pavement design and analysis. The disadvantage is that the layer-by-layer inversion modulus method cannot be directly used to determine the modulus of each layer of the existing road, which should be tracked and tested from the construction period. In the future, the application of the layer-by-layer inversion method should be verified through more on-site work points and pavement structure types.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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