Analysis of Loading Stress of Pavement Structure using One-Step Forming Cement-Stabilized Macadam Base

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Abstract: Layered construction of large thickness cement-stabilized macadam base makes the base change from designed being forced by whole layer to being forced by two thin layers, the existence of interfacial friction between two thin layers reduces the pavement performance of the base, which finally cause the reduction of pavement performance of whole pavement structure. To analyze the load responses of large thickness cement-stabilized macadam base asphalt pavement under different working conditions, pavement surface deflection, maximum principal stresses of surface layer bottom and base layer bottom, minimum principal strain of soil base top and maximum shear stress of surface layer bottom under two different working conditions(layered construction and one-step forming) are taken as indexes and are obtained by finite element analysis method in this paper.

1 Introduction

Cement-stabilized macadam asphalt pavement is widely used in construction of high-grade highway in china, and with the increasing traffic volume and axle load, the thickness of the base layer will reach more than 30cm [1-3]. Limited by machinery, layered construction is generally used in base construction. But, inconsistent with the pavement structure design concept that the base should be forced by whole layer, layered construction makes the base change from being forced by whole layer to being forced by two thin layers, thus serious stress concentration occurred between two layers, and the pavement performance and service life are reduced as a result[4-7]. With the appearance of ultra wide paver and large-tonnage roller, it is possible to realize the full-thickness construction technology of cement-stabilized macadam base. Compared with the layered construction of large thickness cement-stabilized macadam base, full-thickness construction has better pavement performance (Tian et al., 2014). In this paper, pavement surface deflection, maximum principal stresses of surface layer bottom and base layer bottom, minimum principal strain of soil base top and maximum shear stress of surface layer bottom under two different working conditions(layered construction and full-thickness construction) are taken as indexes to analyze the mechanical responses of layered construction technology and full-thickness construction technology[8-10].

2 Mechanical analysis model

In this paper, rectangular load is adopted as load model because the researches show that more accurate interaction between tire and road surface could be simulated by rectangular load form than by double circle load form which is adopted by current asphalt pavement design specifications [11-13]. Load model for dual rectangular sized 16.667cm×21.3cm, 31.95cm dual rectangular center distance (Liao & Huang, 2008). Standard axleload (100KN single axle double wheel load) is used as wheel load, its surface force is $P=0.7\text{MPa}$, the horizontal load of the vehicle when the vehicle is running is $F=\lambda P$. According to the experience, take $\lambda=0.015$, so the horizontal load F is 0.0105 MPa. In this paper, two kinds of working conditions of the large thickness cement-stabilized macadam base asphalt pavement are simulated to analyze: Under first condition a 35cm large thickness base layer is divided into two layers, the upper base layer is 17cm and the lower is 18cm, considering the interlayer contact, take $\mu=0.5$. The second condition is full-thickness construction technology of large thickness cement-stabilized macadam base, and we adopt 35cm, 33cm, 31cm, 29cm, 27cm and 25cm these six different thicknesses to compare with condition 1, respectively. The plane size of the model is 3.81m * 3.81m, and the thicknesses are actual sizes. The schematic diagram of the geometric model and the mesh are shown in Fig.1 and Fig.2, the boundary conditions are as follows: Z direction

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displacement is $U_3=0$, X direction displacement is $U_1=0$,
 Y direction displacement is $U_2=0$.

Figure 1. Geometric model

Figure 2. Mesh

Table 1. The material parameters and thickness of each pavement structure layer

Structure Type	Modulus (MPa)	Thickness (cm)	Poisson's Ratio
Asphalt surface layer	1800	18	0.25
Upper base layer	1300	17	0.25
Lower base layer	1300	18	0.25
Graded broken stone base layer	300	25	0.25
Soil base	40	300	0.35

3 Mechanical response analysis of pavement structure under two different working conditions

3.1 Pavement surface deflection

Pavement surface deflection is vertical displacement of whole pavement structure under load, which reflects the resistance to deformation of whole pavement structure and so is the total stiffness of the pavement structure, the smaller pavement surface deflection is, the stronger the resistance to deformation of whole pavement structure is. Fig.3 and Fig.4 are pavement deflection nephograms of condition 1 and condition 2(35cm), respectively. Fig.5 is graph of pavement deflection change along the road transverse (the horizontal line as shown in Fig.3) under two kinds of conditions. [14-15].

According to Fig.5, whether using layered construction technology or full-thickness construction

technology in base layer construction, the pavement deflection value curves are inverted W shape. In the full-thickness construction technology of cement-stabilized macadam base, the maximum pavement deflection value decreases with the increase of the thickness of the full-thickness base layer, when the thickness increases to a certain extent, the reduction of maximum pavement deflection turns slowly although the thickness of base layer keeps increasing.

Extracting maximum deflection value from curves derived from ABAQUS, we can see that maximum pavement deflection under condition 1 is $4.026 \times 10^{-4} \text{m}$ and maximum pavement deflection under condition 2 (35cm) is $3.242 \times 10^{-4} \text{m}$, under the same base layer thickness of 35cm, the maximum deflection value of the layered construction technology is 1.24 times of the full-thickness construction technology. In addition, according to the curves, maximum pavement deflection value under condition 2(27cm) is $3.941 \times 10^{-4} \text{m}$, which is still less than that under condition 1.

Figure 3. Pavement deflection nephogram of condition 1

Figure 4. Pavement deflection nephogram of condition 2

Figure 5. Pavement deflection change graph of different conditions

3.2 Maximum principal stresses of the bottom of the surface layer and the base layer

In the pavement structure design specification of China, the tensile stress(strain) of the bottom of the surface layer and the bottom of the base layer are taken as the design criteria of fatigue cracking, when the tensile stress produced by the load exceeds the ultimate tensile stress (tensile strain) of the material, the fatigue crack will occur[16-17]. In this paper, maximum principal stress determined by six normal stresses and shear stresses is adopted as index to analyze pavement structure under two kinds of construction conditions, because the maximum principal stress is greater than the maximum horizontal principal stress, the maximum principal stress as an analysis index is on the safe side. Fig.6 is the maximum principal stress nephogram of the cross-section of the pavement structure under working condition 1, and Fig.7 is the maximum principal stress nephogram of the cross-section of the pavement structure under working condition 2(35cm).

From Fig.6 and Fig.7, we can see that the surface layer bear the maximum compressive stress under wheel loads, with the increase of the depth, compressive stress decreases gradually and finally change into tensile stress, and we can see that stress mutations appear in the position of interlayer contact and where pavement structure material changes. In the case of pavement structure under condition 1, the upper and middle surface layer are under compressive stress, and it begins to appear tensile stress in lower surface layer, what's more, the maximum tensile stress appears between the upper base layer and the lower base layer; For second condition (35cm) full-thickness base pavement, the upper, middle and lower surface layer are in compression, it is in the base layer that the tensile stress begins to occur and the maximum tensile stress appears at the bottom of the base layer, what's more, the maximum principal stress of the bottom of the base layer under condition 1 is only 52.5% of the maximum principal stress of the base layer under condition 2. Thus it can be known that the existence of interlayer contact has a great influence on the maximum principal stress of the bottom of the base layer.

Fig.8 is the graph of the maximum principal stress change of the bottom of the surface layer along the road transverse under two different working conditions. Fig.9

is the graph of the maximum principal stress change of the bottom of the base layer along the road transverse under two different working conditions.

Figure 6. The maximum principal stress nephogram of the cross-section of the pavement structure under working condition 1

Figure 7. The maximum principal stress nephogram of the cross-section of the pavement structure under working condition 2(35cm)

Figure 8. The graph of the maximum principal stress change of the bottom of the asphalt surface layer under Different kinds of conditions

Figure 9. The graph of the maximum principal stress change of the bottom of the base layer under different kinds of conditions

From Fig.8, we can see, for condition 2 full-thickness base layer, with the increase of the thickness of the base layer, the maximum principal stress of the bottom of the asphalt surface layer decreased gradually, and it distributes more uniformly along the pavement transverse, this is because the larger the thickness of the base layer is, the larger the stiffness of the base layer is. Therefore, it can distribute the stress area more uniformly, and if the thickness turns smaller, then the stiffness turns smaller, thus relatively large stress will appear in the area under the direct load. In addition, the maximum stress value of the bottom of the asphalt surface layer under condition 1 is much larger than that under condition 2(35cm), the maximum principal stress value of the bottom of the asphalt surface layer under condition 1 is $4.81 \times 10^4 \text{ Pa}$, while that value under condition 2(35cm) is $1.61 \times 10^4 \text{ Pa}$ which is only 33.5% of that under condition 1. And it is found that the maximum principal stress of the bottom of the surface layer under condition 2 (25cm) is $4.36 \times 10^4 \text{ Pa}$, which is still less than that under condition 1.

From Fig.9 we can see, for condition 2 full-thickness base layer, with the increase of the thickness of the base layer, the maximum principal stress of the bottom of the base layer also showed a decreasing trend, and the reduction is smaller and smaller, which indicates that the contribution of further increase of the thickness of the base layer to reduce the maximum principal stress becomes small. In addition, the maximum principal stress of the bottom of the upper base layer under condition 1 is much larger than the maximum principal stress of the bottom of the base layer under condition 2(35cm), but the maximum principal stress of the bottom of the lower base layer under condition 2(35cm) is very small. Obtained from the graph, the maximum principal stress of the bottom of the upper base layer under condition 1 is $1.659 \times 10^5 \text{ Pa}$, and that under condition 2(35cm) is $8.707 \times 10^4 \text{ Pa}$, which is only 52.5% of condition 1, this is because the stress concentration phenomenon appears due to the existence of the interlayer contact between upper

base layer and lower base layer under condition 1, therefore the maximum principal stress of the bottom of the upper base layer is relatively large.

3.3 The minimum principal strain of the top of the soil base

The strain at the top of the subgrade is a very important index to reflect the safety and stability of the subgrade [18-20]. Phenomenon of subsidence and rutting will appear if the strain of the top of subgrade is too large, the maximum compressive strain (minimum principal strain) is taken as the evaluation index to compare and analyze the pavement structure under two different kinds of working conditions in this section. Fig.10 and Fig.11 are the minimum principal strain nephograms of condition 1 and condition 2(35cm), respectively. Fig.12 is the graph of the minimum principal strain change along the road transverse (the horizontal line as shown in Fig.12) under two kinds of conditions.

From Fig.12 we can see, for condition 2 full-thickness base layer, with the increase of the thickness of the base layer, the minimum principal strain of the top of the soil base decreases gradually, and the reduction is smaller and smaller which indicates that the contribution of further increase of the thickness of the base layer to reduce the minimum principal strain becomes small. In addition, the minimum principal strain of the top of the soil base under condition 1 is -2.699×10^{-4} , while the minimum principal strain of the top of the soil base under condition 2 is -1.875×10^{-4} , which is only 69% of that under working condition 1, indicating that the existence of the interlayer contact has certain influence on the minimum principal strain of the top of the soil base. We also find that the minimum principal strain of the top of the soil base under condition 2(29cm) is -2.615×10^{-4} , which is also less than that under condition 1.

Figure 10. The minimum principal strain nephogram of the top of the subgrade under Condition 1

Figure 11. The minimum principal strain Nephogram of the top of the subgrade under condition 2

Figure 12. The graph of the minimum principal strain change along the road transverse under two kinds of conditions

3.4 The maximum shear stress of the bottom of the asphalt pavement surface layer

Shear stress is an important factor in asphalt surface shear failure and interlayer slippage, a very small shear stress could cause the asphalt pavement surface shear failure especially in high temperature season. In this section, the maximum shear stress of the asphalt surface layer is taken as a index to compare and analyze the pavement structure under two different kinds of working conditions. Fig.13 and Fig.14 are the maximum shear stress nephograms of condition 1 and condition 2(35cm), respectively. Fig.15 is the graph of the maximum shear stress of the bottom of the surface layer change along the road transverse (the horizontal line as shown in Fig.13) under two kinds of conditions.

Known from Fig.15, the maximum shear stress of the bottom of the asphalt pavement surface under condition 1 is $3.61 \times 10^5 \text{ Pa}$, the maximum shear stress of the bottom of the asphalt pavement surface under condition 2(35cm) is $2.77 \times 10^5 \text{ Pa}$ and is only 77% of that under condition 1, indicating that the existence of the interlayer contact increases the shear stress of the bottom of the asphalt pavement surface layer and finally reduces the pavement performance. And to condition 2 full-thickness base layer, with the increase of the thickness of the base layer, there do have a relatively weak increase in the shear stress of the bottom of the asphalt pavement surface, and increases smaller and smaller. Therefore, to reduce the thickness of the base layer in a certain extent is helpful to reduce the maximum shear stress peak of the bottom of the asphalt pavement surface.

Figure 13. The maximum shear stress of the bottom of the asphalt surface layer nephogram under condition 1

Figure 14. The maximum shear stress of the bottom of the asphalt surface layer nephogram under condition 2(35cm)

Figure 15. The graph of the maximum shear stress of the bottom of the surface layer change along the road transverse (The horizontal line as shown in Fig.13) under two kinds of conditions

4 Conclusion

The load stress response analysis of the indexes of pavement surface deflection, maximum principal stresses of surface layer bottom and base layer bottom, minimum principal strain of soil base top and maximum shear stress of surface layer bottom under two different working conditions with large thickness cement-stabilized macadam base are performed in this study. The main conclusions are as follows:

1) The pavement deflection under condition 2(35cm) is 80% of that under condition 1, even the pavement deflection under condition 2(25cm) is better than that under condition 1, through the comparison of two kinds of working conditions with the pavement deflection as the evaluation index.

2) The maximum principal stress of the bottom of the surface layer under condition 2(35cm) is only 33% of that under condition 1, even the maximum principal stress of the bottom of the surface layer under condition 2(25cm)

is less than that under condition 1, through the comparison of two kinds of working conditions with the maximum principal stress of the bottom of the surface layer as the evaluation index.

3) The maximum principal stress of the bottom of the base layer under condition 2(35cm) is only 52.5% of that under condition 1, even the maximum principal stress of the bottom of the base layer under condition 2(25cm) is less than that under condition 1, through the comparison of two kinds of working conditions with the maximum principal stress of the bottom of the base layer as the evaluation index.

4) The minimum principal strain of the top of the soil base under condition 2(35cm) is only 69% of that under condition 1, even the minimum principal strain of the top of the soil base under condition 2(29cm) is less than that under condition 1, through the comparison of two kinds of working conditions with the minimum principal strain of the top of the soil base as the evaluation index.

5) The maximum shear stress of the bottom of the surface layer under condition 2(35cm) is only 77% of that

under condition 1, even the maximum shear stress of the bottom of the surface layer under condition 2(25cm) is less than that under condition 1, through the comparison of two kinds of working conditions with the maximum shear stress of the bottom of the surface layer as the evaluation index.

6) According to the analysis of the rule of each index changing with the base layer thickness, the increase of the thickness of the base layer has a favorable trend to these indexes except that the shear stress of the bottom of the asphalt surface layer has a relatively weak increase with the increase of the thickness of the base layer. Thus obtained from the above comparison, the mechanics indexes of the full-thickness cement-stabilized macadam base pavement is far higher than that of the layered cement-stabilized macadam base pavement, and even the mechanics indexes of the full-thickness cement-stabilized macadam base (29cm) is better than that of the layered cement-stabilized macadam base.

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