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Dynamic response of concrete pavement structure with asphalt isolating layer under moving loads

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Abstract: A three-dimensional finite element model (3D FEM) is built using ABAQUS to analyze the dynamic response of a concrete pavement structure with an asphalt isolating layer under moving loads. The 3D model is prepared and validated in the state of no asphalt isolating layer. Stress and deflection at the critical load position are calculated by changing thickness, modulus of isolating layer and the combination between the isolating layer and concrete slab. Analysis result shows that the stress and deflection of the concrete slab increase with the increase of thickness. The stress and deflection of the concrete slab decrease with the increase of combination between the isolating layer and concrete slab. The influence of changing the isolating layer modulus to the stress and deflection of the concrete slab is not significant. From the results, asphalt isolating layer design is suggested in concrete pavement.

Key words: concrete pavement; asphalt isolating layer; moving loads; three-dimensional finite element

1 Introduction

Asphalt isolating layer is paved on the top base of concrete pavements, which can effectively avoid the pumping, fill void under the concrete slab, and ultimately avoid disruption due to concrete slab damage (Yao 2003; Deng 2005; Liao et al. 2010). Currently asphalt isolating layer is gaining more attention, but it is more challenging to properly pave it in concrete pavement. Chen et al. researched the mechanical properties of concrete pavement with different isolation layers on lean concrete base, and the wax was recommended as the isolation layer between concrete pavement slab and lean concrete base (Dziewański et al. 1980; Chen et al. 2009; Yao et al. 2012). Tarr et al. analyzed interlayer bonding conditions between different bond breaker media and concrete slabs and found bond breaker media had significant impacts

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on pavement stresses (Tarr et al. 1999; Fu 2004). There is lack of stress analysis under moving loads. In the existing design methods of concrete pavement, equivalently simplified vehicle load is commonly known as a static uniform load. Static uniform load is most commonly used on pavement structure for the mechanical analysis and calculation and that is basically reasonable on the condition of low speed and small load. In fact, moving vehicles on the road produce a complex vertical force and horizontal force to the pavement. Actually, there is a great difference between static loads mode and moving loads mode on pavement slab. Under the fast-moving vehicle loads, the response of concrete pavement structure cannot be described by the static mechanical characteristics (Hou et al. 2003; Kim and McCullough 2003; Yang 2005; Wang and Yang 2008; Liang 2011). For the concrete pavement with an asphalt isolating layer under the concrete slab, it is necessary to calculate and analyze the response of pavement structure under moving loads, and the results are benefitial to design the asphalt isolating layer in concrete pavement.

2 Establishment of 3D model

In this paper, the moving vehicle loads are considered as surface loads which have a certain speed. ABAQUS 3D finite-element analysis software is used to establish concrete pavement structure model with the asphalt isolating layer (Wang and Chen 2006; Liao and Huang 2008; Cao and Shi 2009; Zhuang et al. 2009; Wang and Fu 2010). The size of cement concrete slab is 4.50 m ×3.75 m, and the slab thickness is 22 cm. The thickness of asphalt isolating layer ranges from 0 to 3 cm. Subgrade depth is gradually expanding to 2.0 m, while the stress in the slab is convergence, and this size is used in the subsequent calculation, the whole pavement structure is shown in Fig. 1.

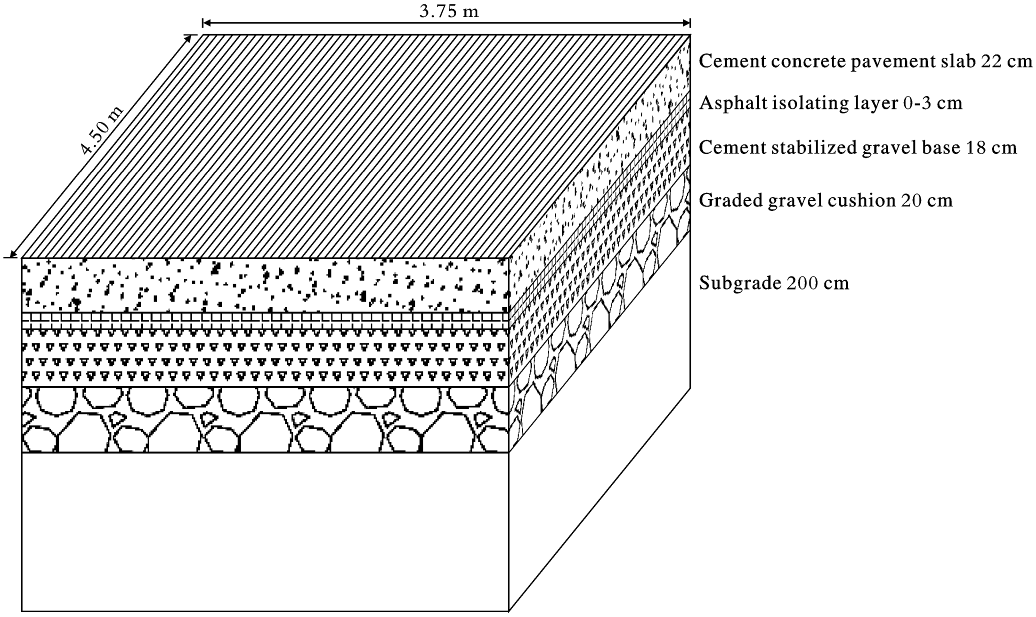


Fig. 1 Concrete pavement structure

2.1 Calculation parameters

Material parameters of each structure layer are determined by reference to the Specifications of Cement Concrete Pavement Design for Highway (JTG D40-2002), α and β are damping constants and the damping matrix C is calculated by using these constants to multiply the mass matrix M and stiffness matrix K.

$$C = \alpha M + \beta K \tag{1}$$

In this paper, the value of α and β are taken according to the research work of Liao and Huang (2008) and Liu (2010). As β is zero (Liu 2010), it is not listed in the table. Other parameters are shown in Tab. 1.

Tab. 1 Parameters in dynamic response analysis

Pavement structure	Modulus of elasticity E(MPa)	Poisson's ratio μ	Density ρ(kg/m^3)	Damping constant α
Cement concrete pavement slab	31000	0.15	2400	0.05
Aspahlt isolating layer	1200	0.25	2400	0.40
Cement stabilized gravel base	1500	0.25	2300	0.80
Graded gravel cushion	250	0.35	2300	0.40
Subgrade	50	0.40	1800	0.40

3D pavement is used as linear 8-node 3D solid model in finite element model(Cheng 2006; Sheng et al. 2012). It is assumed that material parameters do not vary with temperature. Each node has 6 degrees of freedom: 3 translational degrees of freedom and 3 rotational degrees of freedom. 3D FEM is calculated with linear reduction compression integral unit. Pavement layer is considered as half spatial elastic space. Asphalt isolating layer is treated as homogeneous elastic thin layer. The contact between asphalt isolating layer and cement stabilized gravel layer, the contact between cement stabilized gravel layer and cushion, and the contact between cushion and subgrade are all fully continuous.

2.2 Constraint condition and mesh generation

In ABAQUS 3D finite element model, fixed constraint is imposed to bottom of the subgrade on 3D pavement structure model, which means constraints are imposed in the direction of X, Y, and Z. The horizontal constraints are imposed to the side of the asphalt isolating layer, base course and subgrade, which means constraints are imposed in the direction of X and Z. To simulate with actual road conditions of the concrete pavement slab, tie bars are embedded in the middle side of the longitudinal joints (length × spacing × diameter: 70 cm × 75 cm × 18 mm). One end of tie bar is embedded and bonded in the concrete pavement slab (the vertical bonding stiffness of tie bar and cement concrete K_s = 30 MPa/mm, tangential friction coefficient is 0.2(Appalaraju 2003; Davids et al. 2003; Wang 2007; Jiang and Zhang 2009), the other end of the tie bar is fixed constraint, and the interaction between adjacent slabs is not considered except the tie bar.

The grid size used in 3D FEM is 0.06 m × 0.06 m, the grid of concrete pavement slab in vertical is divided into 8 layers, the grid of cement stabilized gravel base in vertical is divided into 2 layers, the grid of graded gravel cushion in vertical is divided into 2 layers, and the subgrade in vertical is divided into 6 layers in accordance with the 1∶2, as shown in Fig. 2. The grid size of tie bar is 0.02 m × 0.02 m, size in longitudinal direction is 0.04 m. 3D model grid of tie bar is shown in Figs. 3(a) and 3(b).

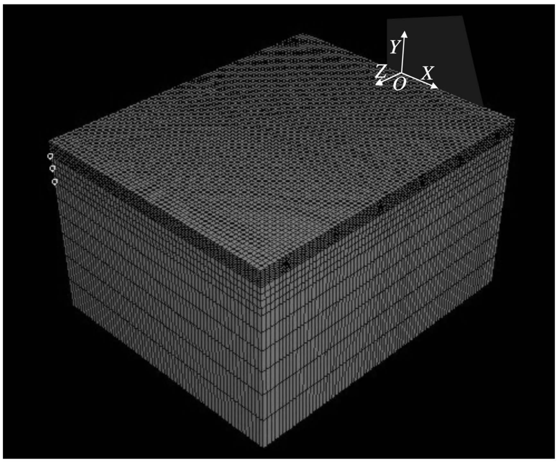
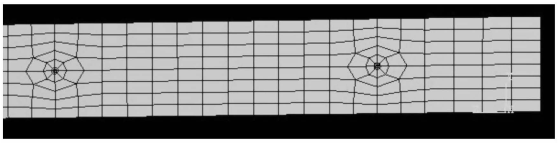
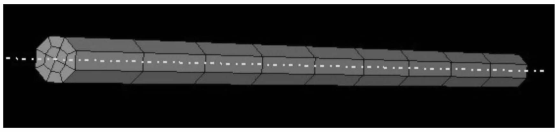


Fig. 2 Mesh of 3D finite element model



(a) Mesh model of tie bar in side of concrete slab longitudinal joints



(b) Mesh model of tie bar

Fig. 3 Mesh model of concrete pavement with tie bar

2.3 Model validation

In order to validate the pavement model, a solution under static load is calculated by using the method of the Specifications of Cement Concrete Pavement Design for Highway (JTG D40-2002). This method is based on elastic thin slab on the half space elastic foundation theory, and compared with the results by the 3D finite element model. During the calculation, all the pavement layers are completely continuous and there is no asphalt isolating layer. The stress and deflection of critical position (central part in longitudinal joint) from static standard axle loads (100 kN) are shown in Tab. 2.

Tab. 2 Verification of finite element model calculation

Computing projects	Calculation solution(no tie bar)	Calculation solution(with tie bar)	Solution of specification
Deflection at critical position (mm)	0.3562	0.05353	—
Maximum stress at critical position (MPa)	1.1790	1.03100	1.2010

The solutions of specification method and finite element method are compared in critical positions. It is shown that the tensile stress is about 1.75% in critical position. The tensile stress reduced by 12.72% after the tie bar was embedded in finite element model, and the stress reduction factor of tie bar is 0.873. In the specifications of cement concrete pavement, the stress reduction factor of tie bar is 0.87-0.92 (low value is at rigid and semi-rigid base, high value at flexible base). The results of finite element are acceptable. In addition, the deflection calculated by the finite element model is roughly the same as the test results of concrete pavement (Yao 2003). From the validation, the finite element model is correct.

3 Characteristics of moving loads

A standard axle load of BZZ-100 is considered as the moving load, which is simplified as a rectangular uniformly distributed surface load (Huang 1998; Feng 2008). BZZ-100 has single axle, double tires, tire pressure is 0.7 MPa, and the total axle load is 100 kN. Rectangle of 0.1568 m ×0.2277 m is determined by vehicle tire test on pavement. The moving load zone is established by the vehicle load move direction. The vehicles are limited to the moving load zone, as shown in Fig. 4. The width of the moving load zone is 0.1568 m, which is same as the width of uniformly distributed surface loads. The driving distance of wheel loads is the length of the moving loads zone along the longitudinal panel, and the moving loads zone is divided into some small rectangles in order to get loading easily. The length of small rectangle is determined by the calculation, which is taken by one-third of the wheel loads equivalent ground length. In this paper, wheel loads equivalent ground length is 0.2277 m, therefore the small rectangle length is 0.0759 m.

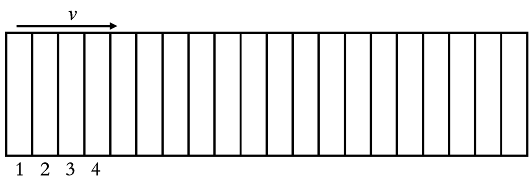


Fig. 4 Moving load zone

The wheel load occupies three rectangular areas 1, 2 and 3 in the initial stage, as shown in Fig. 4. When the load gradually moves forward along the moving direction, a series of loads different analysis steps are set up. At the end of each load analysis step, the whole load moves forward to a small rectangular area. For example, on the end of the first load analysis step, load will occupy the areas of 2, 3, 4. At the same time, in order to improve the accuracy of the calculation, multiple load analysis sub-steps are set up in each load analysis step. For example, in the first load analysis step, the use of the load analysis substeps is to gradually decrease the load on the area 1, and gradually increase the load on the area 4, the moving load is analyzed by this method. The speed of moving load is calculated through setting the time of each load analysis step. Speed v is constant in normal driving, and the time is same for every passing small rectangle. So the time can be calculated by the following formula

$$t = \frac{\Delta s}{v} \tag{2}$$

where Δs is width of each rectangle.

In this paper the full system matrix (i. e. full solving method) and the semi-sinusoidal excitation (Jiang and Zhang 2009) are used in dynamic response analysis. The mathematical model of half-sine load function is used on the node of tires contact as follow

$$P(t) = P_{\max}\sin^2\left[\frac{\pi(t-t_0)}{T}\right] \quad t\in[t_0,\ t_0+T] \tag{3}$$

where $P(t)$ is tire load strength imposed on the node at time t, MPa; $P_{\max}$ is maximum load strength of the tire on the node, $P_{\max} = 0.7$ MPa; t_0 is the moment of tire coming to contact with the node; T is the cycle of tire contact with the node.

The process of tires movement in a node of the road is shown in Fig. 5 which shows that the small solid ellipse under the straight line on the node location is affected by moving loads. The dotted line circle location represents the front edge of the tire entering into node contact. The solid line circle represents back edge tire location at tire leaving the node. Vehicles moving speed is v, the arrow represents the direction of the moving vehicle, and a represents the length of the area of tire contact to the ground. The time of tire contact with a node is a/v. Therefore, the effect time of moving loads at different speeds applied to the node can be calculated. The calculation results are shown in Tab. 3.

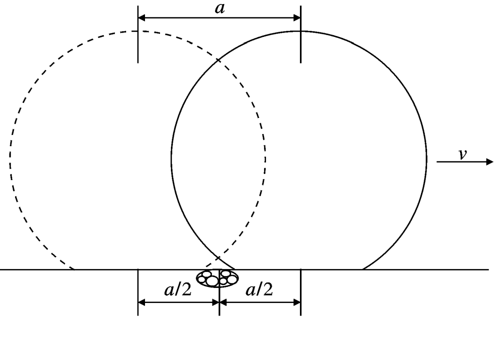


Fig. 5 Process of tires passing the node

Tab. 3 Relationship of speed and effect time of moving load

Vehicle speed (km/h)	40	80	120
Vehicle speed (m/s)	11.111	22.222	33.333
Effect time (s)	0.017	0.009	0.006

In the calculation of 3D finite element method, the moving loads are applied to the longitudinal edge of cement concrete slab, moving from the one end of the slab to the other end at speed v. The geometric diagram of the moving loads on the cement concrete slab is shown in Fig. 6.

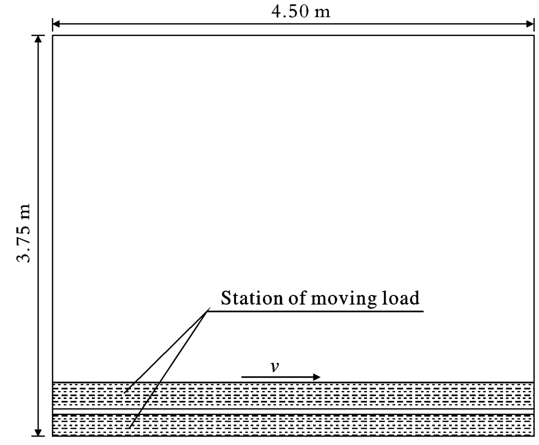


Fig. 6 Station of moving load in finite element model

4 Finite element analysis of dynamic response of moving loads

4.1 Dynamic response analysis with different thicknesses of asphalt isolating layer

The model is prepared based on the parameters of Tab. 1 and Fig. 1, the combining factor of asphalt isolating layer and concrete slab is considered as 1.5 (Yang 2005; Liu 2010). The isolating layer modulus is 1200 MPa. The moving load speed is 40 km/h. The dynamic response of concrete pavement structure is calculated by changing the thickness of isolating layers. The detail results are shown in Tab. 4, Figs. 7 and 8.

When the thickness of isolating layer increases from 0 to 3 cm, the deflection at critical position increases by 11.58%, maximum stress at critical location increases by 18.10%. This indicates that when the combining asphalt isolating layer modulus and load moving speed are fixed, the maximum stress and deflection at critical position of the slab increases with the increase of the thickness of isolating layer. The reason is that asphalt isolating layer is a weak interlayer leading to greater deformation and maximum stress. That means the increase of the thickness of isolating layer is detrimental to the deflection and the maximum stress at critical position. Therefore, in order to decrease dynamic response of concrete pavement structure with asphalt isolating layer, the thickness of asphalt isolating layer should be relatively small.

Tab. 4 Stress and deflection of pavement with different thicknesses of asphalt isolating layer

Computing projects	Thickness of isolating layer (cm)			
	0	1	2	3
Deflection at critical position (10^{-2} mm)	4.093	4.365	4.506	4.657
Maximum stress at critical position (MPa)	0.7067	0.7562	0.7951	0.8346

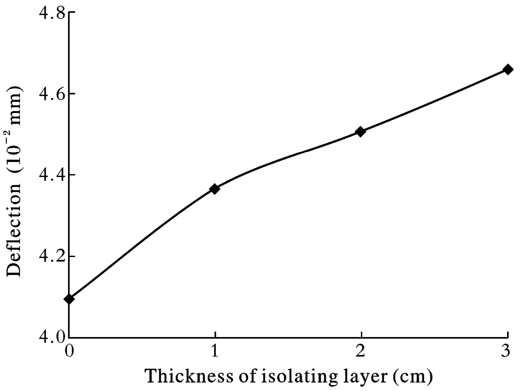


Fig. 7 Deflection at critical position with different thicknesses of isolating layer

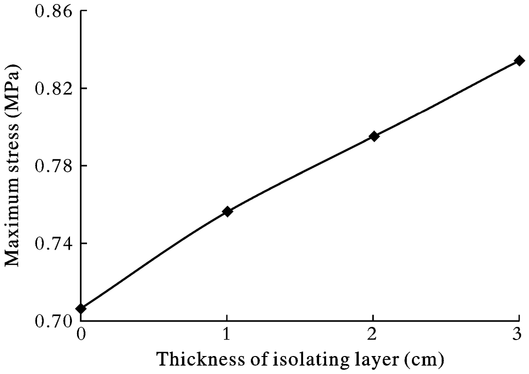


Fig. 8 Maximum stress at critical position with different thicknesses of isolating layer

4.2 Dynamic response analysis with combination between asphalt isolating layer and concrete slab

Friction factor is important to analyze dynamic response between cement concrete slab and semi-rigid base. The friction coefficient is usually from 1.5 to 2.0 (Tarr et al. 1999; Tan et al. 2007). Therefore, the combination between the interface layers translates into the interlayer friction by using the friction coefficient of contact surfaces. In this research, the space surface-to-surface contact analysis model of ABAQUS is used. In this model, two surfaces are used, one is target surface and the other is contact surface. Usually, for the contact surface of rigid and flexible, the rigid surface is defined as the main surface, and the surface with larger deformation compared with the rigid surface is defined as the subordinate surface. So, the cement concrete slab is defined as the main surface, the semi-rigid base or asphalt isolating layer is defined as the subordinate surface.

The thickness of asphalt isolating layer is 1 cm, modulus of asphalt isolating layer is 1200 MPa, the load moving speed is 40 km/h. The dynamic response of concrete pavement structure is calculated by changing the friction coefficient between asphalt isolating layer and concrete slab. The results are shown in Tab. 5, Figs. 9 and 10.

When the friction coefficient changes from 0 to 3, the deflection at critical position reduces from 0.04490 mm to 0.04232 mm, a 5.75% decrease, and the stress at critical position reduces from 0.7773 MPa to 0.7279 MPa, a 6.36% decrease. This indicates that when the isolating layer thickness, isolating layer modulus and speed of the moving load are fixed, the maximum stress and deflection at critical position decrease with the increase of combination between the asphalt isolating layer and the pavement slab. This is because the higher friction coefficient is good to achieve the completely continuous contact between the pavement layers, and the bending stiffness is improved. So the stress and strain can be effectively reduced.

Tab. 5 Stress and deflection of pavement with the combination between asphalt isolating layer and concrete slab

Computing project	Friction coefficient				
	0.0	1.0	1.5	2.0	3.0
Deflection at critical position (10^{-2} mm)	4.490	4.407	4.365	4.321	4.232
Maximum stress at critical position (MPa)	0.7773	0.7634	0.7562	0.7490	0.7279

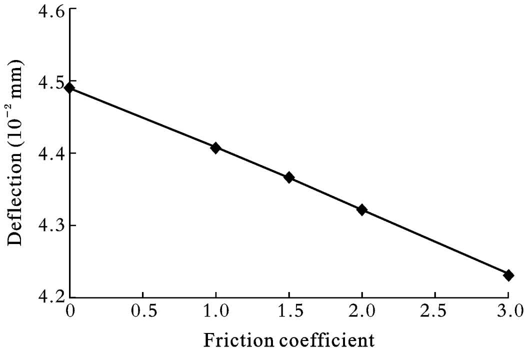


Fig. 9 Deflection at critical position with different friction coefficients

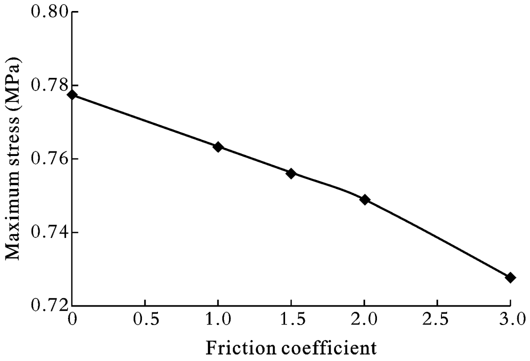


Fig. 10 Maximum stress at critical position with different friction coefficients

4.3 Dynamic response analysis with different moduli of asphalt isolating layer

Dynamic response is analyzed on different moduli of asphalt isolating layer. The thickness of asphalt isolating layer is 1 cm, the friction coefficient between the isolating layers is 1.5, the load moving speed is 40 km/h. The dynamic response of concrete pavement structure is calculated by changing modulus of the asphalt isolating layer. The results are shown in Tab.6.

From Tab.6, when asphalt isolating layer modulus increases, the deflection at critical position reduces slightly. When asphalt isolating layer modulus increases from 800 MPa to 2000 MPa, the deflection at critical position reduces by 0.75%. The maximum stress at critical position also slightly reduces, and the maximum stress reduces by 1.81%. This indicates that the change of the asphalt isolating layer modulus has no significant effect on the maximum stress and deflection at critical position. It is because the thickness of the asphalt isolating layer is relatively small.

In theory, the higher the modulus of the asphalt isolating layer, the better for the deflection and the maximum stress at critical position, but the impact of changing the asphalt isolating layer modulus is not significant on the deflection and the maximum stress. The increase of asphalt isolating layer modulus is affected on cost, so the isolating layer modulus should not be too high.

By analyzing the calculation results, it shows that three influence factors generally affect the dynamic response of concrete slab. They are the thickness, the combination, and the modulus of asphalt isolating layer. Among three influence factors, the isolating layer thickness has the most significant impact, then the combination follows, and the impact of isolating layer modulus has least impact.

5 Recommendation of thickness and materials

According to the previous analysis of calculation results, the thickness of asphalt isolating layer should be relatively small in order to decrease dynamic response of concrete pavement structure with asphalt isolating layer, but the asphalt isolating layer should achieve the waterproofing requirement. Asphalt isolating layer should have enough water resistance, low temperature performance and durability. In addition, the construction convenience and roughness should be taken into account. Therefore, the asphalt isolating layer should have enough thickness. Considering functional requirements of dynamic response of the concrete slab, construction requirement, and cost factors, the appropriate thickness of asphalt isolating layer is proposed as 1-2 cm.

Tab. 6 Stress and deflection of pavement with different moduli of asphalt isolating layer

Computing project	Modulus of isolating layer (MPa)			
	800	1200	1600	2000
Deflection at critical position (10^{-2} mm)	4.381	4.365	4.356	4.348
Maximum stress at critical position (MPa)	0.7592	0.7562	0.7502	0.7456

Higher friction coefficient between the combining asphalt isolating layer and the concrete slab is better to reduce the stress and deflection of the concrete slab. In addition, as the recommended thickness of asphalt isolating layer is 1-2 cm, asphalt isolating layer materials would be selected as asphalt treatment, micro-surfacing, cape seal, fine-aggregate asphalt concrete, sand asphalt, synchronous crushed stone seal, because these materials can provide higher friction.

The thickness of asphalt treatment, micro-surfacing, synchronous crushed stone seal can be controlled within 1-2 cm, and these kinds of layers do not affect the pavement structure. These materials can prevent the water permeability or erosion, and improve roughness(Li 2005). In addition, these materials have a big texture depth after paving. At the same time, by selecting the sticky asphalt or polymer modified asphalt, it is easy to achieve waterproof performance and to control the modulus of asphalt isolating layer, and the construction of such materials is convenient, rapid and low cost. So, asphalt treatment, micro-surfacing, synchronous crushed stone seal are recommended for the asphalt isolating layer.

6 Conclusions

Stress and deflection at critical position are calculated by changing thickness, modulus of isolating layer and the combination between the isolating layer and concrete slab. Dynamic three-dimensional finite element model (3D FEM) of ABAQUS is applied to analyze the dynamic response of concrete pavement structure with asphalt isolating layer under moving loads. The summarizing results of study are as follows.

In the concrete pavement with asphalt isolating layer, the bending stress and deflection at critical position increase with the increase of the asphalt isolating layer thickness, and decrease with the increase of combination between asphalt isolating layer and concrete slab. But when changing the asphalt isolating layer modulus, stress and deflection are not significantly different. In these three factors, the asphalt isolating layer thickness has the most significant impact.

According to the calculation results of the dynamic analysis of a pavement structure under moving loadings, a thickness of asphalt isolating layer of 1-2 cm is recommended. Asphalt treatment, micro-surfacing, and synchronous crushed stone seal are recommended to asphalt isolating layer.

Acknowledgments

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