FEM analysis of dynamic behavior of asphalt pavement structure weakened by grassroots with account of hydraulic and vehicle load coupling effects

J Huang¹², X Pan¹, S B Dai¹² and Y Cai¹³

¹School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China
²Design & Research Institute, Wuhan University of Technology, Wuhan 430070, China

E-mail: clovya@whut.edu.cn

Abstract. This paper establishes the finite element model of saturated asphalt pavement with ANSYS. The thickness and elastic modulus of pavement surface layers and grassroots are taken as influencing factors to analyze the influence of these factors’ change on the pavement mechanical behavior. The results indicate that the increase of surface thickness leads to the shear stress’s decrease that may relieve the internal shear stress concentrated phenomenon effectively. The increase of elastic modulus of surface makes the pore pressure decrease, and result in the shear stress’s increase. The grassroots thickness has no obvious effect on the pore-water pressure and shear stress; the grassroots elastic modulus’ increase may increase the internal shear stress and decrease the pore pressure.

1. Introduction

As a kind of porous medium, the asphalt mixture is shape-complex, randomly filled and has porosity. Therefore, the pavement structure of asphalt mixture is of a certain permeability [1, 2]. Existing results indicate that the asphalt pavement in saturated water state is the most vulnerable to damage [3, 4]. When the vehicle passes through the water-covered pavement, water, which failed to be discharged in time, will produce enormous pore-water pressure in a short period. This kind of pore-water pressure will cause washing and squeeze to pavement structure that may cause the asphalt mixture in the pavement structure to lose the adhesive strength and peel off easily, causing the pavement damage [5]. Also, the presence of the shear stress also can induce pavement rutting damage [6]. Therefore, It’s necessary to understand the dynamic behavior of asphalt pavement structure under the action of hydraulic and vehicle coupling effect. Also, in-depth study of the changing rule of the pavement mechanical response to pavement material parameters changes is essential. That can provide theoretical basis for damage prevention and control of pavement structure.

The research of moisture-loading coupling effect of asphalt pavement started in the 1960s. Hunter has carried on the related research [7] about the hydraulic seepage law of asphalt pavement and arrived at a conclusion that when the diameter of the permeation apparatus is small or the grassroots is thick the deviation of the permeability of the pavement will be great.

³ Address for correspondence: Y Cai, School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China. E-mail: clovya@whut.edu.cn.
Kringos adopted a new modeling approach to study the phenomenon that the pore-water pressure of the asphalt pavement may result in the loss of the cohesive force of the aggregate. Through the study, Kringos made a great achievement about the interrelation between the cohesive force of the aggregate and the pore-water pressure.

Krishnan studied the interrelation between permeability coefficient and porosity of the asphalt pavement. He held that the movement of the mixed particles in the asphalt leads to water damage of the pavement and established the particle motion equation [8].

Although, many splendid achievements about this field have been achieved, the current researches about seepage field and stress field coupling effect are incomplete. For instance, multi physical field coupling and more precise simulation of the pavement are still remained to be explored.

This paper, by using ANSYS finite element software to simulate saturated asphalt pavement which is under the vehicular action, analyzes the influence exerted by thickness’ change of the surface and grassroots and elastic modulus’s variation on pavement dynamic behavior.

2. The establishment of finite element model

2.1. Analysis model and boundary conditions

Because the pavement depth and length of the driving direction is infinite, the pavement in this case cannot be simulated by software. To guarantee the accuracy of the calculation, avoid a tedious calculation, the paper adopts 2 dimension plane model of 3 x 3 m as the analysis model. As shown in figure 1, in structural layer thickness direction, the model from top to bottom are upper layer, mid-surface, lower layer, grassroots, sub-base and subgrade, and the layer thickness are respectively 0.04 m, 0.06 m, 0.08 m, 0.36 m, 0.20 m and 2.26 m.

Boundary conditions of the model are as follows: The boundary of the model in the horizontal direction has been established, but the boundary can be mobilized in the vertical direction and is waterproof. The upper boundary of the model is established in the horizontal direction but free in the vertical direction. Except the load region, the rest region is permeable. The lower boundary of the model is waterproof, and established in the horizontal direction and the vertical direction. Based on the schematic diagram of the model, this paper established the finite element model with ANSYS.

2.2. Basic parameters of pavement structure material

The density, Poisson's ratio, elastic modulus, saturated permeability coefficient and other parameters of each layer of the pavement structure model are shown in table 1.
Table 1. Parameters of each layer of the structure.

| Name of each layer | Density/(g/cm³) | Poisson ratio | Modulus of elasticity/MPa | Saturation permeability coefficient (m/s) |
|--------------------|----------------|--------------|---------------------------|------------------------------------------|
| upper layer        | 2.64           | 0.30         | 1400                      | 4.8×10⁻⁵                                 |
| mid-surface        | 2.55           | 0.35         | 1200                      | 1.75×10⁻⁵                               |
| lower layer        | 2.52           | 0.35         | 900                       | 1.25×10⁻⁵                               |
| grassroots         | 2.2            | 0.20         | 1600                      | 1.23×10⁻⁷                               |
| sub-base           | 2.2            | 0.30         | 350                       | 2.65×10⁴                                |
| subgrade           | 1.65           | 0.40         | 40                        | 3.32×10⁻⁹                               |

2.3. The dynamic load of the driving vehicle

The vehicle’s dynamic load model is an approximate simulation of the process of vehicle running. Due to the circular uniformly distributed load is accordance with the actual situation of ordinary vehicle wheel’s incentive. Therefore, according to the current rules and regulations, the vehicle load is simplified as double circular uniformly distributed vertical load [9] which is presented in figure 2.

When the vehicle drive down the road, the load’s acting time on the pavement is very short., sinusoidal-load is adopted to simulate the driving load, the maximum circular uniformly distributed vertical load is \( P_{\text{max}}=0.7 \text{MPa} \), the time of the single acting driving is \( T \). During the analysis time, the uniformly distributed load value function is as equation (1) [10]. The driving speed is 90 km/h that is fixed and immovable, the load time is 0.05 s, and the analysis time is \( T=0.25 \text{s} \).

\[
p = \begin{cases} 
  P_{\text{max}} \sin \left( \frac{\pi}{T} t \right) & 0 \leq t \leq 0.05s \\
  0 & 0.05s \leq t \leq 0.25s 
\end{cases}
\]

3. The influence of the surface layer material

3.1. The influence of surface layer thickness

In this section, surface’s thickness is taken as influencing factor. The paper considers five groups of layer thickness to analyze the pavement surface’s mechanical response to different layer thickness’s influence. Specific combinations situations are shown in table 2, except the layer thickness values, other parameters are presented in table 1.

Table 2. Surface layer thickness

| surface layer thickness/m | combination 1 | combination 2 | combination 3 | combination 4 | combination 5 |
|---------------------------|--------------|--------------|--------------|--------------|--------------|
| upper layer thickness/m   | 0.03         | 0.04         | 0.05         | 0.06         | 0.07         |
| mid-surface thickness/m   | 0.05         | 0.06         | 0.07         | 0.08         | 0.09         |
| lower layer thickness/m   | 0.07         | 0.08         | 0.09         | 0.10         | 0.11         |
| Total thickness of surface layer/m | 0.15 | 0.18 | 0.21 | 0.24 | 0.27 |

As shown in figures 3 and 4, the figures are respectively the changing rule of the maximum pore-water pressure and shear stress in the surface layer structure under the condition of different thickness of surface layer. From figure 3, we can see the maximum pore-water pressure value of the surface layer’s bottom increases monotonically with the increase of the surface layer’s thickness. The maximum pore-water pressure of the bottom layer increased from 72.875 to 103.1 KPa when the
surface layer’s thickness increased from 0.12 to 0.3 m, rising by about 41% or so.

**Figure 3.** The influence of surface layer thickness on the maximum pore-water pressure in pavement.

**Figure 4.** The influence of surface layer thickness on the maximum shear stress in pavement.

From figure 4, it can be seen that the thicknesses of the surface layer has a great effect on the shear stress, and the maximum shear stress decreases with the increase of the surface layer’s thickness. When surface layer’s thicknesses are 0.15 m and 0.27 m, the maximum shear stress of pavement structure is 235.92 KPa and 199 KPa. Stress concentration phenomenon in the pavement is effectively relieved. This suggests that the surface layer can hinder the force’s wave-form transfer, and layer’s thickness is the key factor of hindering effect.

### 3.2. The influence of surface layer modulus

In this section, five groups of surface layer modulus are selected as contrast factor to analyze the influence of modulus change on the mechanical behavior of Asphalt Pavement. Its surface layer modulus are in turn 800 MPa, 1000 MPa, 1200 MPa, 1400 MPa and 1600 MPa. Except the surface layer modulus values, other parameters are presented in table 1.

As shown in figures 5 and 6, the figures are respectively changing rule of the maximum pore-water pressure and shear stress in the surface layer structure under the condition of different surface layer modulus. As shown in figure 5, the maximum pore-water pressure of the bottom layer decreased from 92.046 to 73.45 KPa when the surface layer modulus values increased from 800 to 1600 MPa. When modulus is small, the effect of modulus change on pore-water pressure change is more obvious. The maximum shear stress in surface layer increases with the modulus, but the increase is slight, the shear stress only increases from 223.16 to 241.28 KPa.

**Figure 5.** The influence of surface layer modulus

**Figure 6.** The influence of surface layer modulus
modulus on the maximum pore-water pressure in pavement. on the maximum shear stress in pavement.

4. The influence of grassroots materials

4.1. The influence of grassroots thickness

In this section, grassroots thickness is taken as influencing factor to analyze the influence of different grassroots thicknesses on pavement surface structure’s mechanical response. The grassroots thicknesses respectively are 0.32 m, 0.36 m, 0.40 m, 0.44 m and 0.48 m. Except grassroots thickness values, other parameters are presented in table 1.

As shown in figures 7 and 8, the figures are respectively changing rule of the maximum pore-water pressure and shear stress in the surface layer structure under the condition of different thickness of grassroots. Figure 7 shows that when the grassroots thickness increased, the change range of the maximum pore-water pressure is basically between 80 and 85 KPa, the change is almost negligible. This is mainly because the permeability coefficient of grassroots is much smaller than surface layer’s permeability coefficient. Thus, water is still concentrated in the surface layer structure and will not penetrate more moisture to the grassroots. Therefore, the change of grassroots thickness will not affect the pore-water pressure in the surface layer structure significantly. As shown in figure 8, when grassroots thickness increases from 0.32 to 0.48 m, the maximum shear stress of surface layer decreases from 239.94 to 200.6 KPa, and the variation of shear stress is consistent with the change of grassroots thickness.

![Figure 7](image1.png) ![Figure 8](image2.png)

Figure 7. The influence of grassroots thickness on the maximum pore-water pressure in pavement. Figure 8. The influence of grassroots thickness on the maximum shear stress in pavement.

4.2. The influence of grassroots modulus

In this section, the grassroots modulus is taken as the influencing factor to analyze the influence of modulus change on the mechanical behavior of Asphalt Pavement. The grassroots modulus are respectively 1000 MPa, 1200 MPa, 1400 MPa, 1600 MPa and 1800 MPa. Except the surface layer modulus values, other parameters are presented in table 1.
Figure 9. The influence of grassroots modulus on the maximum pore-water pressure in pavement.

As shown in figures 9 and 10, the figures are respectively changing rule of the maximum pore-water pressure and shear stress in the surface layer structure under the condition of the different grassroots modulus. As shown in figure 9, the maximum pore-water pressure of the bottom layer decreases from 84.31 to 80.98 KPa when the grassroots modulus increases from 1000 to 1800 MPa, the variation of pore-water pressure is small. Also, the influence of grassroots modulus change on the maximum shear stress of the surface layer bottom is not obvious. When grassroots modulus increases, the shear stress increases from 222.82 to 229.88 KPa, and, along with the grassroots modulus’s increase, the shear stress gradually tends to saturation.

5. Conclusions
By using ANSYS finite element software to simulate saturated asphalt pavement that is under vehicular action, the paper analyzed the influence of thickness’ change of the surface layer and grassroots and elastic modulus’s variation on pavement dynamic behavior. The following conclusions can be drawn:

- When the surface layer thickness increases, the pore-water pressure in the surface layer correspondingly increases which is disadvantageous for pavement resistance to water-induced damage. The surface layer can hinder the force’s wave-form transfer, and, layer’s thickness is the key factor of the hindering effect.
- The increase of modulus of the surface layer reduces the pore-water pressure. Therefore, the control of surface layer materials’ elastic modulus is important for the pavement to resist the erosion of the pore-water.
- The change of grassroots thickness mainly affects the shear stress of pavement structure, but, the change of pore-water pressure is not obvious. The maximum shear stress in the structure of the surface layer decreases with the increase of the grassroots thickness.
- The change of grassroots modulus has little effect on the shear stress of pavement structure and the pore-water pressure.

Acknowledgments
This material is based upon work supported by the open subject foundation (grant no. DQJJ201301) of the Key Laboratory of Road Bridges and Structural Engineering of Hubei Province (Wuhan University of Technology).

References
[1] Wei P K 2012 Damage of concrete asphalt pavement under hydrodynamic pressure (Chongqing Jiao tong University, Chongqing, China: PhD Thesis)
[2] Dong Z J, Tan Y Q and Cao L P 2007 Research on pore pressure within asphalt pavement under the coupled moisture-loading action *Journal of Harbin Institute of Technology* **39** 1614-7

[3] Xu B 2003 *Theory and Practice of Drainage Asphalt Pavement* (Shanghai: Tongji University Press)

[4] Liu R J 2013 Dynamic response analysis of asphalt pavement under moving load (Shijiazhuang Tiedao University, Shijiazhuang, China: PhD Thesis)

[5] Sun L J 2003 *Asphalt Pavement Structure Behavior Theory* (Shanghai: Tongji University Press)

[6] Chen F F, Huang X M and Shan J S 2008 Mechanical analysis of different asphalt pavement under over loading *Shanghai Highways* **2** 11-5

[7] Hunter A E and Airey G D 2005 Numerical modeling of asphalt mixture site permeability *The 84th Annual Meeting of the Transportation Research Board* (Washington)

[8] Krishnan J M and Rao C L 2001 Permeability and bleeding of asphalt concrete using mixture theory *International Journal of Engineering Science* **39** 611-27

[9] Sha A M 2011 *Roadbed Engineering* (Beijing: Higher Education Press)

[10] Yu L 2013 Study on porous asphalt pavement structures for urban road (Hunan University, Changsha, China: PhD Thesis)