Finite Element Analysis of Asphalt Pavement on Account of Stress-seepage Coupling Field

Chundi Si

Institute of Transportation Environment and Safety Engineering, Shijiazhuang Tiedao University, Shijiazhuang 050043, Hebei, China

Chunyan Si*

Office of Principle, Hebei University of Engineering, Handan 056038, Hebei, China

Yang Feng

Institute of Transportation Environment and Safety Engineering, Shijiazhuang Tiedao University, Shijiazhuang 050043, Hebei, China

Yang Wang

School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang 050043, Hebei, China

Abstract
The coupling water-load action is one of the primary factors of initial damage in asphalt pavement. In this paper, the coupling mechanism of stress and seepage field is introduced, by using the finite element numerical analysis software ABAQUS, a viscoelastic constitutive model of asphalt pavement is established. The pore water pressure and saturation in asphalt pavement under the action of seepage field is analyzed, and the dynamic response of asphalt pavement under stress field and stress-seepage coupling field is compared, including vertical displacement, vertical stress, longitudinal stress, transversal stress and shear stress. The result indicates that under the action of seepage field, the change trend of pore water pressure and saturation is that increasing first and then decreasing with the extension of rainfall duration, in comparison with the stress field, the stress-seepage coupling field is more easily to create crack and permanent deformation of asphalt pavement.
Key words: ROAD ENGINEERING, ASPHALT PAVEMENT, FINITE ELEMENT SIMULATION, STRESS-SEEPAGE COUPLING FIELD, PORE WATER PRESSURE, SATURATION, DYNAMIC RESPONSE

1. Introduction

Because of long-term exposure to rain, snow and complex environmental conditions, and in recent years, the phenomenon of overloading is more and more serious, the asphalt pavement disease frequently occurs, such as rut, pit, crack and so on. The occurrence of the disease not only increases the maintenance cost, but also influences the performance of the pavement. It is generally believed that the main factor causing early damage of asphalt pavement is the action of dynamic water pressure acting on the pavement under the vehicle load[1,2].

Many scholars have carried out a lot of research on the water damage of asphalt pavement. Through field test, the characteristics of water flow in asphalt pavement are analyzed by Pratico[3]. Raab, C. et al analyze the effect of moisture on interlayer bonding of asphalt pavements[4]. Based on the theory of interface, the adhesion and water damage model of asphalt on the surface of the mine is established, and the influence of the surface energy parameters on the water damage process is discussed by Xiao Qingyi et al[5]. Wang Duanyi et al use digital image processing technology to detect and evaluate the surface segregation of asphalt pavement, and the degree of water damage in the asphalt pavement wheel track test is forecasted[6]. However, these performance evaluations of asphalt mixture water damage are often standard tests[7], do not break away from the traditional water stability evaluation methods and process, and also lack the consideration of environmental factors. In view of the asphalt pavement structure can be regarded as the fluid solid two-phase medium, the mechanical response analysis of asphalt pavement under the coupling effect of water and load is developed based on the porous media theory[8,9]. But these researches are often directly deal with the pavement in full water state, the research considering the actual rainfall infiltration condition is rarely reported[10].

Based on layered viscoelastic theory, by using of the finite element numerical analysis software ABAQUS, this paper establishes the asphalt pavement structure model. The changes of pore water pressure and saturation under different rainfall time are analyzed by applying the seepage field on the pavement structure model, then moving load is applied on the pavement, the response of asphalt pavement under stress field and stress-seepage coupling field is compared, thus the influence of water on asphalt pavement is explained.

2. Coupling mechanism of stress field and seepage field

2.1 The interaction between stress field and seepage field

2.1.1 Effect of seepage filed on stress field

When the water head difference exists in the pavement, the water body the seepage movement will produce, that is the hydrodynamic pressure. The dynamic water pressure is mainly in the form of seepage flow, its influence to stress field is mainly by changing the distribution of the stress field in the pavement[11]. The seepage volume force is related to the hydraulic gradient, according to the knowledge of seepage mechanics, the following formula can be obtained.

$$f = \sqrt{f_x^2 + f_y^2 + f_z^2} \tag{1}$$

where, $$f_x = -\gamma_w \frac{\partial H}{\partial x} = \gamma_w J_x \tag{2}$$

$$f_y = -\gamma_w \frac{\partial H}{\partial y} = \gamma_w J_y \tag{3}$$

$$f_z = -\gamma_w \frac{\partial H}{\partial z} = \gamma_w J_z \tag{4}$$

where，f is seepage volume force, f_x, f_y and f_z Are component of seepage force in the x, y and z direction, γ_w is bulk density of water, J_x, J_y and J_z are hydraulic gradient in x, y and z directions of finite element.

2.1.2 Effect of stress field on seepage filed

Stress load will accelerate water repeated pumping function in the pavement, also will strengthen the water to the asphalt membrane replacement and emulsification[12]. The porosity of the pavement will be changed when applied stress field, and the size of porosity directly affects the penetration of the internal waters of the pavement. Therefore, the influence of stress field on the seepage field is mainly reflected in the change of permeability coefficient of pavement[13]. According to Darcy's law,

$$k = k_0 \frac{\rho g}{\mu} = k_0 \frac{\gamma_w}{\mu} = k_0 \frac{g}{v} \tag{5}$$

where， k_0 is permeability, μ is absolute viscosity of water, v is kinematic viscosity coefficient of water.

The relationship between permeability coefficient and porosity[14] can be expressed as,

$$k = k_1 \left\{ \frac{n(1-n_0)}{n_0(1-n)} \right\}^3 \tag{6}$$

where， k is permeability coefficient when porosity is n, k_1 is permeability coefficient when porosity is n_0, n_0 is initial porosity, n is porosity after seepage.

2.2 Basic equations of stress-seepage coupling field

2.2.1 Finite element equilibrium equation of stress field

According to the physical and geometric equations of the element, considering the effect of seepage volume force, the finite element equilibrium equation is established by using the nodal displacements.

$$[K]\{\delta\}=\{F\}+\{P\} \tag{7}$$

where, $[K]$ is structure integral stiffness matrix, $\{\delta\}$ is structure displacement array, $\{F\}$ is external load vector, $\{P\}$ is equivalent load vector.

The structure integral stiffness matrix can be expressed as,

$$[K]=\sum\int[B]^T[D][B]\mathrm{d}v \tag{8}$$

where, $[B]$ is geometric matrix, $[D]$ is elastic matrix.

Geometric equation, $\{\varepsilon\}=[B]\{\delta\}$ (9)

Physical equation, $\{\sigma\}=[D]\{\varepsilon\}=[D][B]\{\delta\}$ (10)

2.2.2 Coupling equation of seepage field and stress field

The finite element equilibrium equation of stress and seepage coupling field can be expressed as,

$$\left.\begin{array}{l} k=k_1\left\{\dfrac{n(1-n_0)}{n_0(1-n)}\right\}^3 \\ [K]\{\delta\}=\{F\}+\{P\} \\ [k][h]+[F]\left[\dfrac{\partial h}{\partial t}\right]=[B] \end{array}\right\} \tag{11}$$

3. Establishment of Finite element model of Asphalt Pavement

3.1 Pavement structure and material parameters

The model structure is derived from the actual pavement structure of a highway in Hebei province, China. The model material parameters are shown in Table 1.

3.2 Geometric modeling

Based on the hypothesis that the plane direction and depth direction of pavement is infinite[15], by using of finite element software ABAQUS, the establishment of road model is as follows: X direction, namely transverse direction is 6 m, Y direction, namely depth direction is 3 m, Z direction, namely longitudinal direction is 8 m. The model is As shown in Figure 1.

Table 1. Pavement material parameters

Pavement structure layer	Thickness /cm	Density /(kg·m^{-3})	Modulus of elasticity /MPa	Poisson's ratio	Damping coefficient		Viscoelastic parameters			
					α	β	g_1	g_2	τ_1	τ_2
Modified fine grained asphalt concrete	4	2500	1600	0.35			0.745	0.255	32206	32.09
Modified medium grained asphalt concrete	6	2500	1400	0.35			0.513	0.487	20790	18.8
Asphalt stabilized macadam	10	2450	1300	0.35			—	—	—	—
Cement stabilized macadam	18	2400	1600	0.20	1.52	0.006	—	—	—	—
Lime-fly ash stabilized macadam	18	2300	1600	0.25			—	—	—	—
Lime-fly ash stabilized soil	20	1800	900	0.20			—	—	—	—
Soil sub-grade	—	1850	30	0.40			—	—	—	—

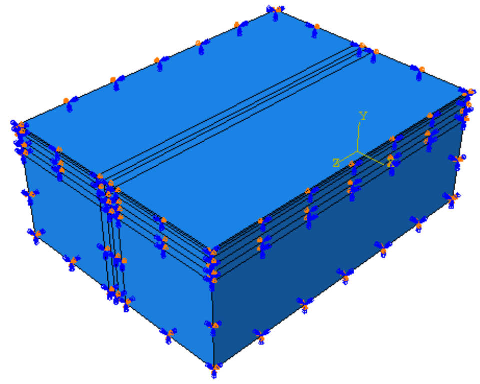

Figure 1. The Geometric model

3.3 Rainfall setting

The groundwater level is considered as below the road surface 5 m, and the rainfall intensity is used to express the rainfall boundary function, the phenomenon of surface water accumulation does not take into account. In ABAQUS finite element model, the rainfall is set by applying load to simulate rainfall, the load type is Surface Pore fluid, the size is 20 mm/h. In the load action place, a time varying amplitude is created to simulate rain, which is shown in Table 2. The pavement structure are affected by rainfall in the whole analysis process, and the rainfall time is 72 h.

Table 2. Relationship between time and amplitude

Time/h	Amplitude
0	0
24	1
48	1
72	0

3.4 Application of moving load

In this paper, the external subroutine function in ABAQUS is used to apply the moving load on the model, a moving load subroutine is written in FORTRAN language, then, the intended mobile function is achieved along the pre-painting moving track. Moving loads are changing with time and space, so in this paper VDLOAD is used to realize the moving load.

4. Calculation result analysis

4.1 Seepage field analysis

By the calculation of the seepage field model, the variation of pore water pressure and saturation in the pavement structure within 72 h can be obtained. The pore water pressure cloud pictures of 12 h, 24 h, 48 h, 72 h are shown in Figure 2- Figure 6.

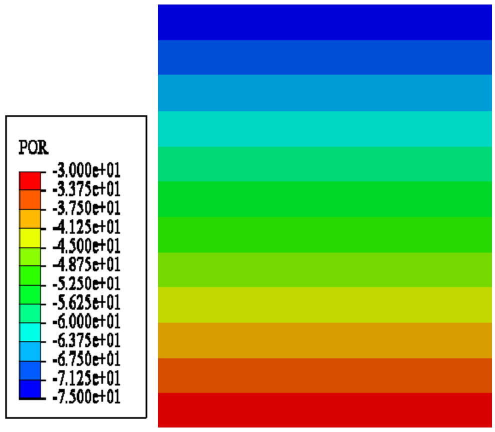

Figure 2. Pore water pressure without rainfall

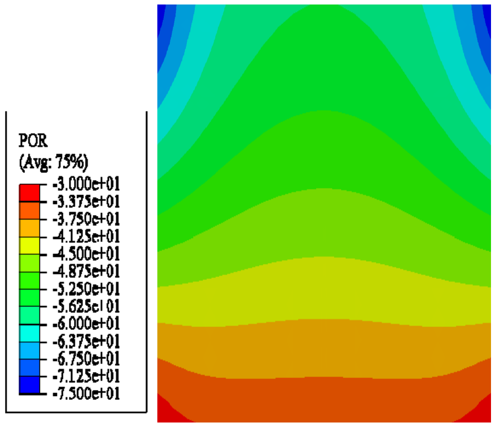

Figure 3. Pore water pressure of 12 h rainfall

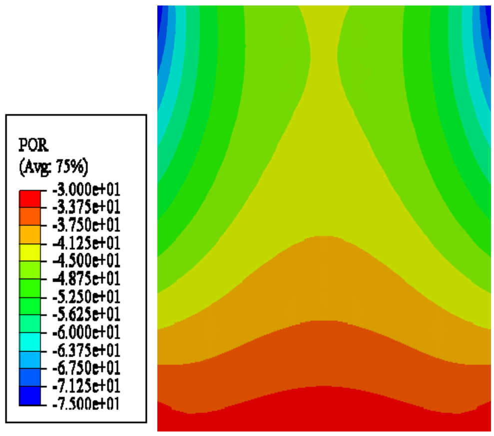

Figure 4. Pore water pressure of 24 h rainfall

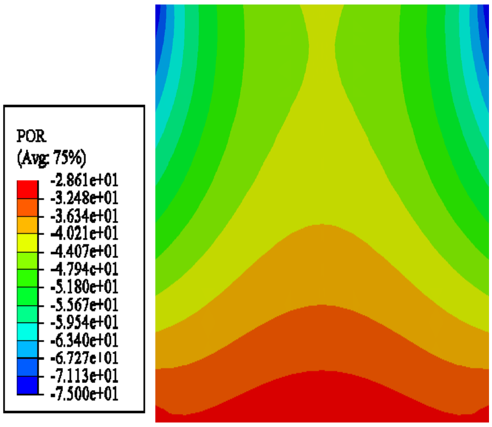

Figure 5. Pore water pressure of 48 h rainfall

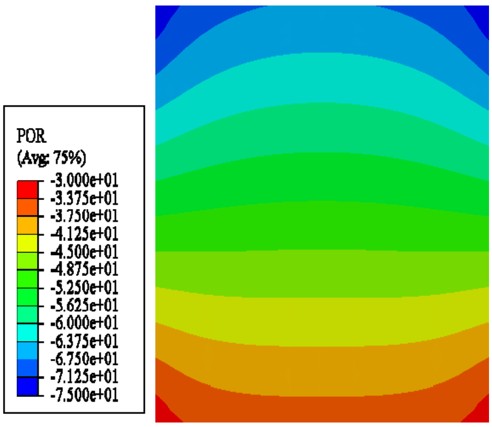

Figure 6. Pore water pressure of 72 h rainfall

It can be seen from Figure 2-Figure 6 that, when no rain, the distribution of pore water pressure is linear, the pore water pressure is expressed as suction, and the pressure value is negative, the pavement surface pressure is -75 KPa, and the bottom pressure is -30 KPa. With the rainfall infiltration, in each structure layer the matrix suction decreases gradually, and the pore water pressure gradually increases. After 48 h rainfall, the pore water pressure reaches -43.6 Kpa. After 72 h rainfall, the pore water pressure gradually decreases with the continuous rainfall infiltration, and the matrix suction is slowly restored. In each pavement structure layer, the pore water pressure shows the trend of increasing first and then decreasing with the increasing of rainfall time. Rainfall 24 h to 48 h, the pore water pressure of each layer has little change.

The saturation cloud pictures of 12 h, 24 h, 48 h, 72 h are shown in Figure 7- Figure 11.

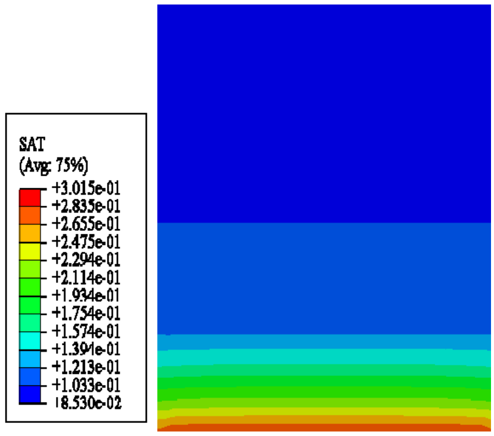

Figure 7. Saturation without rainfall

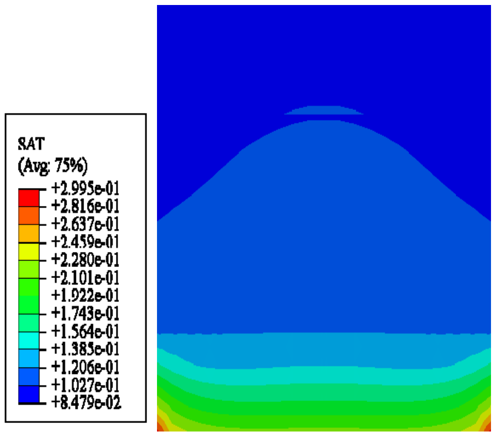

Figure 8. Saturation of 12h rainfall

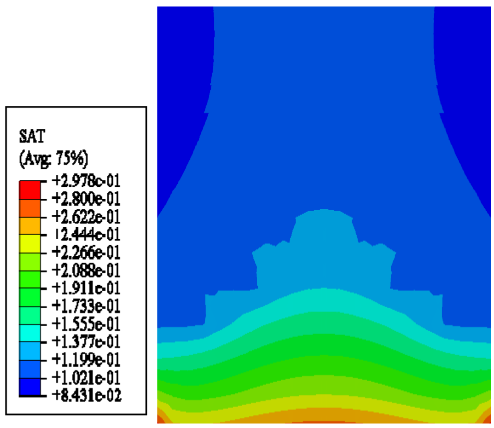

Figure 9. Saturation of 24 h rainfall

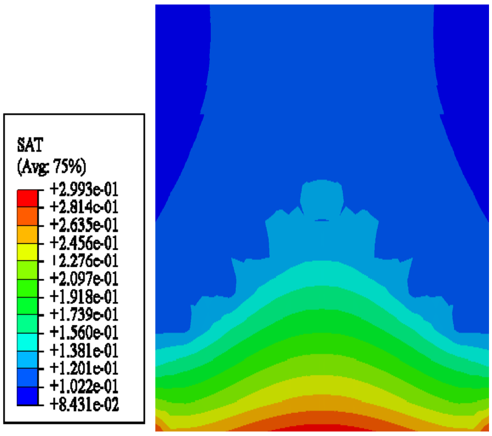

Figure 10. Saturation of 48 h rainfall

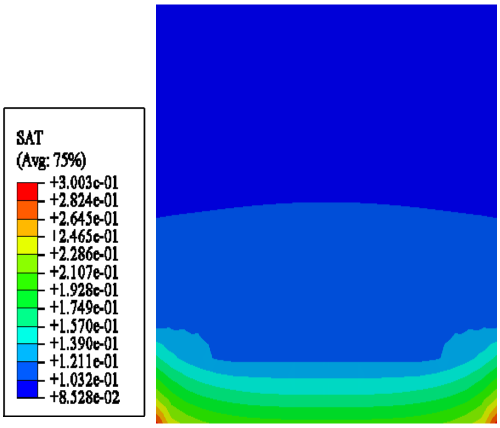

Figure 11. Saturation of 72 h rainfall

It can be seen from Figure 2-Figure 6 that, when no rain, from the top layer to the bottom layer, the saturation is gradually increasing. After the rainfall begin, the saturation gradually increases from the bottom layer, because of the impermeable boundary set on both sides of the model, the saturation in the intermediate position increases faster. After 72 h rainfall, with the infiltration of rainwater, saturation decreases gradually.

4.2 A comparative analysis with stress field and stress-seepage coupling field

Select the most affected structure layers to be analyzed, and the response curves are shown in Figure 12- Figure 16.

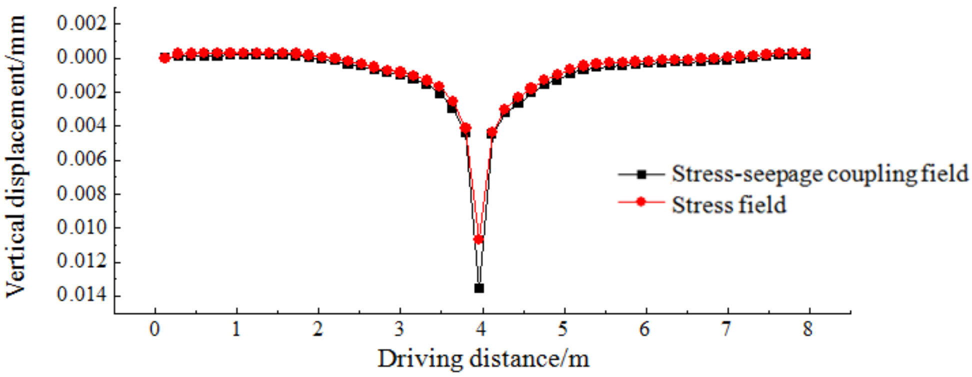

Figure 12. Vertical displacement contrast curve of asphalt upper surface layer

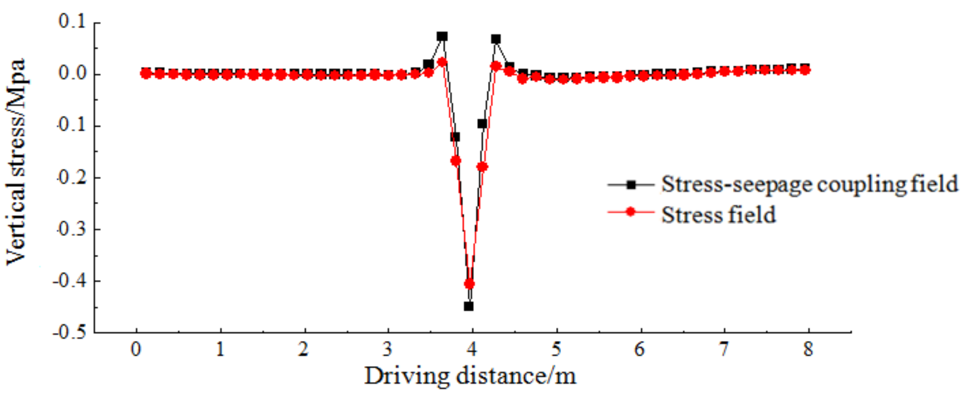

Figure 13. Vertical stress contrast curve of asphalt upper surface layer

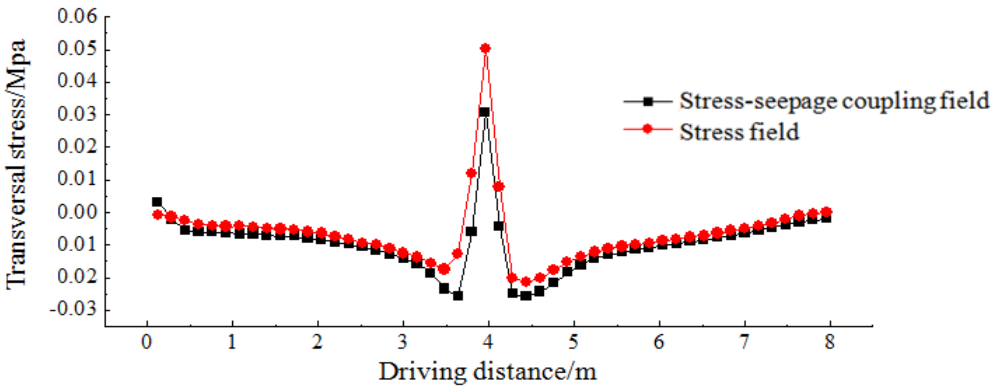

Figure 14. Transversal stress contrast curve of asphalt stabilized macadam layer

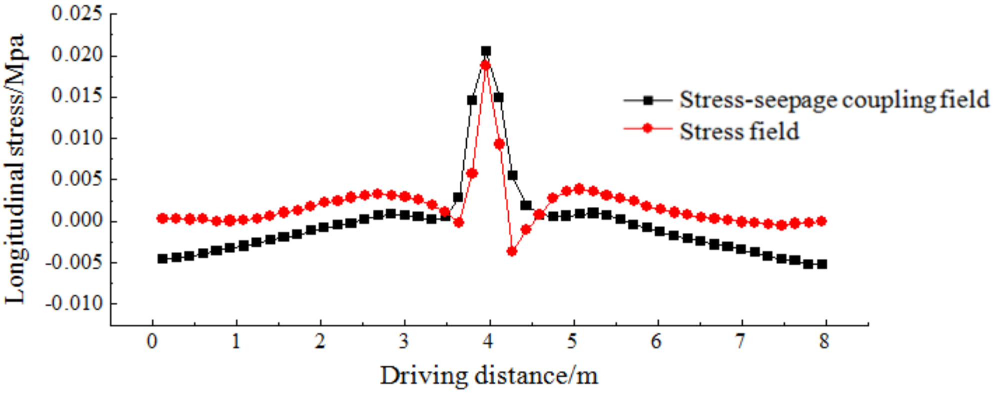

Figure 15. Longitudinal stress contrast curve of asphalt stabilized macadam layer

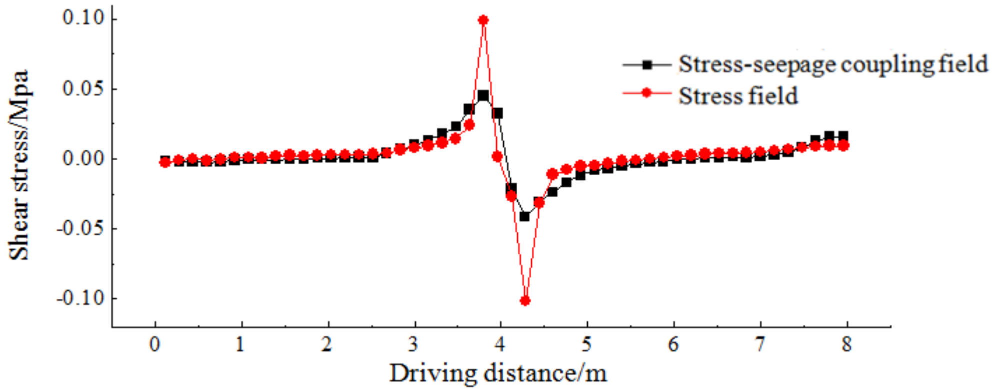

Figure 16. Sheer stress contrast curve of asphalt lower surface layer

The following conclusions can be obtained according to figure 12-figure 16, because of the initial stress applied on stress-seepage coupling model, the initial value of each dynamic response is not 0. In view of vertical displacement, vertical stress and longitudinal stress contrast curve, the response of stress-seepage coupling field is bigger than that of stress field, this shows that in the case of water in the pavement, the surface layer is more easily to produce the compaction deformation, the crack is more likely to be caused by tensile stress in sub base.

From the contrast curve of the transversal stress and shear stress, it can be seen that the response of the stress-seepage coupling field is smaller than that of the stress field, but the effect scope is greater than that of a single field, it's bad for the force of asphalt pavement. That means under the condition of water in pavement, it is more prone to occur the early damage of asphalt pavement.

5. Conclusions

By using of the finite element numerical analysis software ABAQUS, the layered viscoelastic asphalt pavement model is established. The pore water pressure, saturation and dynamic response of asphalt pavement are analyzed.

Under the action of seepage field, with the rainfall infiltration, the pore water pressure and saturation of each layer show the trend of increasing first and then decreasing. After 72 h rainfall, the pore water pressure gradually decreases with the continuous rainfall infiltration, and the matrix suction is slowly restored.

After rainfall, the saturation gradually increases from the bottom layer, because of the impermeable boundary set on both sides of the model, the saturation in the intermediate position increases faster.

In comparison with the stress field, considering the stress-seepage coupling action, the surface layer is more easily to produce the compaction deformation, the crack is more likely to be caused by tensile stress in sub base.

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