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Structural Optimization Analysis of Poroelastic Road Surface Based on Finite Element Technology

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Abstract. Tire road noise is the main component of traffic noise. Therefore, it is of great significance to develop functional pavement which can reduce tire road noise. Poroelastic road surface (PERS) is one kind of high-efficiency noise reduction road structure. In this paper, with the help of finite element technology, the mechanical manners of PERS is simulated, and the flexibility, bending tensile stress/strain, shear stress/strain with different thickness structures were studied and evaluated. The mechanical control indicators of PERS were obtained, meanwhile the semi-flexible pavement structure thickness meeting the demands of pavement mechanics was improved. The conclusion shows that PERS structure can reduce the tensile stress at the foot of the surface layer and improve the driving comfort. It can be used in various structural layers of the highway.

Keyword. Poroelastic Road Surface; Finite element technology; Structural optimization

1. Introduction

PERS is one kind of noise reduction functional road. Different from ordinary asphalt mixtures, rubber particles are used to replace part of aggregate in PERS mixtures, and polyurethane is used as adhesive instead of asphalt. Through the gradation design, the porous structure and sound absorption effect are realized, and the pavement modulus is reduced by rubber particles, which greatly enhances the shock absorption effect of the pavement. Based on the above reasons, PERS has excellent noise reduction functions, as well as good drainage and deicing functions.

PERS generally adopt a large pore structure, with large grained stone occupying most of the pore space. The practical concept of PERS was first put forward by Nilsson of Sweden in the 1970s[1]. He applied for a patent and carried out indoor performance tests on it. The results show that PERS has good noise reduction function. In the 1980s, Swedish researchers carried out limited indoor tests on PERS and paved small-scale outdoor test sections. The test results showed that PERS can achieve 12dB of noise reduction. It is better than conventional noise reduction pavements such as porous asphalt

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pavement, but it also has the problem of insufficient pavement durability. In 1994, Japan Public Works Research Institute[2], based on the research results of noise reduction in Sweden, further carried out the study of outdoor test road. In 1996, S. Meiarashi[3] studied and found that PERS has better effect on road noise reduction than drainage asphalt road surface, and when the vehicle driving speed is above 60km/h, noise reduction for cars and trucks can reach 13dB and 6dB respectively. In 2004, S. Miarashi[4] carried out the test of prefabricated PERS mixture slab. They used the method of prefabricated PERS mixture slab in the room, and then stitched the outdoor test section in the field, and used cement concrete as the underlying layer of the PERS. The results show that the use of polyurethane as the interlaminar binder may lead to insufficient interlaminar bond strength, while the use of epoxy resin can provide sufficient interlaminar bond strength. In 2014, a study on the performance of PERS was conducted by Wang Huoming[5, 6] et al. They found that when the polyurethane content was 5%, the bending and tensile strength were excellent, and the high and low temperature strength were excellent, and when the polyurethane content was too high, the excess binder would fill the voids under the action of gravity, and the strength enhancement would not be greatly affected. Sun Mingxin[7] proposed that the existing calculation formula is not applicable, and the bonding characteristics of polyurethane material is obviously greater than that of asphalt, adopting residual stability, splitting strength ratio and flying loss as the assessment indexes of PERS mixed water stability. Cong Lin[8] et al. are of the opinion that polyurethane mix with 5% content has better spalling resistance and durability than asphalt mix. During the immersion process, it was found that the temperature of the water bath also had a significant effect on the strength of the mixture. Li Xiaoshun[9] was of the opinion that the water stability of PERS is related to the isocyanate content in polyurethane, and the higher the isocyanate content, the higher the brittleness, poor flexibility and poor water stability of polyurethane.

In addition, the superior dewatering performance of PERS is also worthy of attention. Gao Junfeng[10] et al. investigated the water permeability performance of PERS blend and found that the blend has less flying shard loss after immersion, which can meet the specification requirements of OGFC blend. Li Tianshuai[11] and others applied the dynamic crack testing to investigate the permeability of PERS, and discovered that the surface crack strength ratio of PERS mixture was superior to that of asphalt mixture, and the larger the asphalt mixture, the less sensitive to water.

Currently, there is still a shortage of investigation on the structural design of PERS[12,13]. Therefore, this paper will optimize the structural design and put forward the control index through the finite element technology. It provides guidance for structural design, reduces the thickness of the structure layer, saves the construction cost, and improves the popularization and application value of PERS.

2. Study Program and Model Construction

2.1 Study Program

Due to the fact that the mechanical characteristics of PERS are not like traditional bituminous road surfaces., it is essential to carry out the relevant mechanical calculation to analyse the stress condition of PERS in the road structure layer, which provides the theoretical foundation for the application of PERS in bitumen roadway. Consequently, the mechanical characteristics in this numerical simulation, combined with the six common thicknesses of expressway pavement structure layers (Table 1), the next three programs were conducted:

(1) The mechanical evaluation of regular bitumen road uses SBS modified asphalt road for the upper, middle and lower layers.

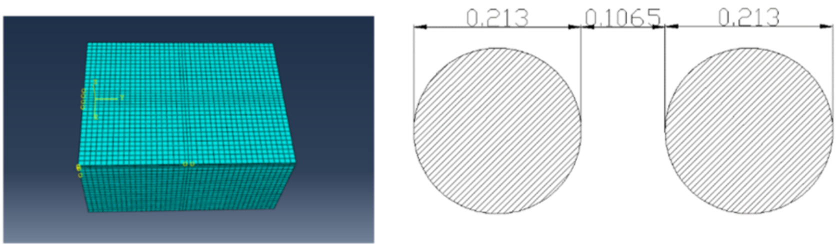
(2) Mechanical calculation of PERS I: the upper layer adopts PERS, and the middle and lower layers adopt SBS modified asphalt pavement;

(3) Mechanical calculation of PERS II: the upper layer adopts PERS, the middle layer adopts high modulus asphalt mixture, and SBS modified asphalt was used to the lower layer.

Table 1. The thickness of each structural layer of the pavement surface (cm)

Structure form	S1	S2	S3	S4
Upper Layer	4	4	4	5
Middle Layer	6	7	8	8
Lower Layer	8	8	8	8
Water Stability Base	36			
Soil foundation	300			

In the calculation, the length of the pavement surface is 5m and the width is 4m. At the same time, The foundations were simulated by expanding the dimensions to represent the features of a semi-infinite space base. The finite element model is illustrated in Figure 1(a).



(a) (b)

Figure 1. 3D model and uniform distribution load

2.2 Loading and Boundary Conditioning

BZZ-100 adopted in current Chinese road design specifications as standard axle load, the wheel ground pressure is 0.7MPa, the radius of the load circles is 10.65cm, with the length of the distance between the centre of the two circles is 31.95cm, and the uniform distribution load of double circles is presented in Fig. 1(b). It is assumed that the surface of the road base is totally fixed, with no lateral and vertical displacement; the road surface and the surrounding roadbed have only vertical displacement.

2.3 Material Parameters

In the calculation and analysis of poroelastic road surface, the modulus of elasticity and Poisson's ratio of asphalt roads surface and porouselastic pavements were determined by indoor tests. The specific characteristics are shown in Table 2.

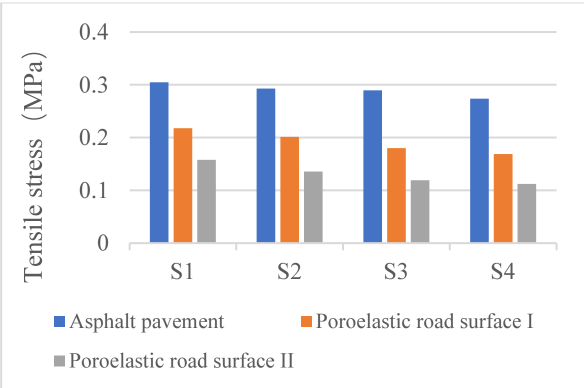
Table 2. The main characteristics of each layer

Structure form	Compression resilience modulus E (MPa)			Poisson's ratio μ		
	asphalt roads surface	PERS I	PERS II	asphalt roads surface	PERS I	PERS II
Upper Layer	1000	200	200	0.30	0.30	0.30
Middle Layer	1250	1250	3000	0.30	0.30	0.30
Lower Layer	1650	1650	1650	0.30	0.30	0.30
Water Stability Base	1850	1850	1850	0.25	0.25	0.25
Soil foundation	70	70	60	0.40	0.40	0.40

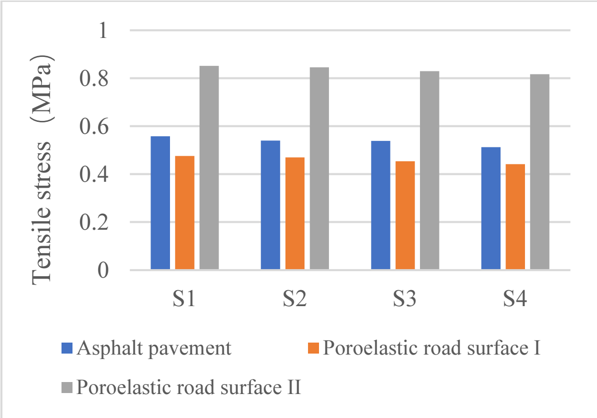
3 Result Discussion

3.1 Stress Analysis

The stresses at the base of the individual layers are calculated with standard load, the affect of the structural scheme on the stress distribution at the foot of each layer is insignificant, the region affected by the stress distribution at the foot of the road surface is a rectangular area of 3m*3m at a gap of 1.5m from the axle load. Taking into account the most unfavourable conditions, the largest stress values at the foot of individual layer are measured for different programs, and the findings are presented in Figures 2~3.

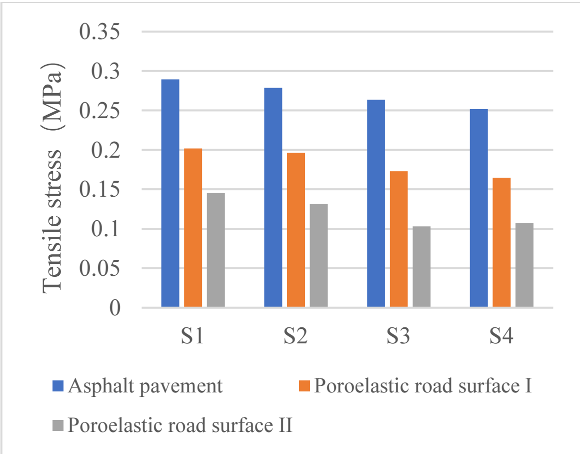


(a) upper layer

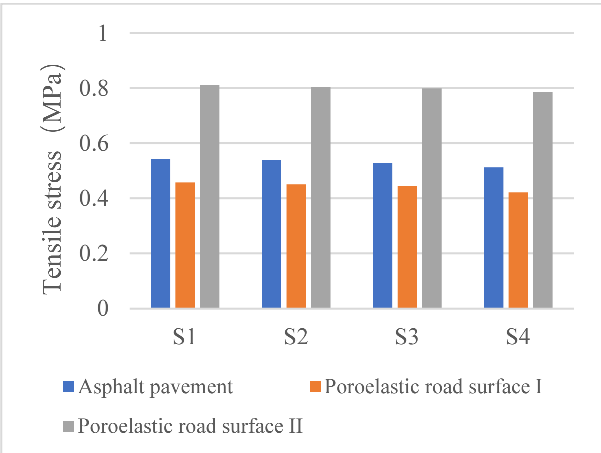


(b) middle layer

Figure 2. Summation graph of horizontal tensile stress



(a) upper layer



(b) middle layer

Figure 3. Summation graph of longitudinal tensile stress

The conclusion that can be made from the study of the figures is as follows:

(1) Under standard axle load, consistent with conventional asphalt pavement, the horizontal tensile stress at the foot of the upper and middle layers of PERS is greater than the longitudinal tensile stress, indicating that the lower layer is more prone to crack in the longitudinal direction than in the horizontal direction under the action of driving load.

(2) According to the calculation results, under standard axle load, the horizontal and longitudinal tensile stresses of the upper layer bottom and the middle layer bottom of the PERS I are lower than those of the conventional asphalt pavement. For PERS II with high modulus asphalt concrete as the middle layer, the horizontal and longitudinal tensile stresses at the foot of the upper layer are the lowest, while the longitudinal tensile stress at the foot of the middle layer becomes significantly larger. But still meet the design requirements.

(3) The application of PERS and high modulus mixture is beneficial to decrease the tensile stress at the foot of the upper layer and improve the structural durability of the functional layer.

(4) Similar to asphalt pavement, in PERS, with the increase of surface layer thickness, the horizontal tensile stress and longitudinal tensile stress of the upper layer and the middle layer bottom gradually decrease. It shows that increasing the thickness of surface layer can effectively reduce the bottom tensile stress of surface layer.

3.2 Displacement Analysis

Considering the most unfavorable situation, the largest top surface displacement of each floor under different programs is measured, and the findings are presented in Figures 4~5.

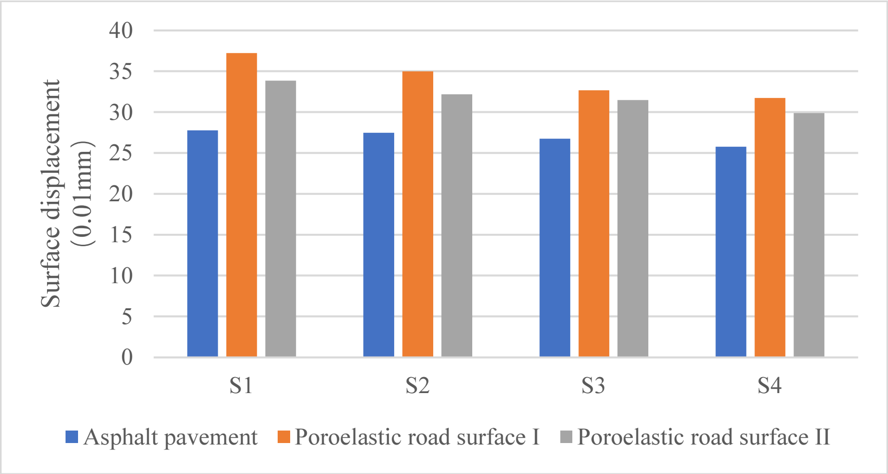


Figure 4. Summation graph of maximum top surface displacement of the upper layer

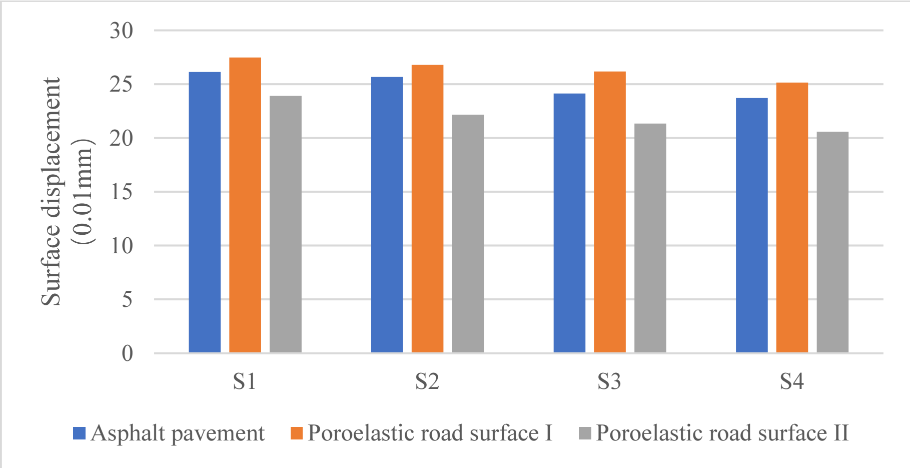


Figure 5. Summation graph of maximum top surface displacement of the middle layer

The following findings can be obtained from the analysis of the data in the figure:

(1) Because the modulus of elasticity of PERS is smaller than that of asphalt mixture, the highest displacements of PERS roads are greater than those of traditional bitumen roads, thus indicating that the PERS structural layer has good vibration absorption capacity.

(2) The largest top surface displacement of the PERS roadway decreases as the standard axle load increases, but the influence is not obvious when compared to a normal pavement structure.

(3) Using high modulus asphalt concrete as the middle surface layer can significantly reduce the largest displacement of PERS top surface.

4 Conclusion

In this article, by establishing a 3D finite element model, using the bottom stress and the maximum vertical top surface displacement as indicators, the mechanical characteristics of PERS structures were analyzed. The major research findings are as listed below:

(1) By making a comparison of the foot stress and vertical top surface displacement of each layer of PERS, the stress and displacement distribution at the foot of each layer is nearly identical as that of ordinary road structures, but with differences in stress and displacement values.

(2) The stress results demonstrated that the horizontal and longitudinal tensile stresses at the foot of the upper and middle layers decreased as the total height of the surface layer increases. Meanwhile, the largest top surface displacement of PERS under standard axle load is larger than that of asphalt pavement, which demonstrates the good damping effect of the PERS structural layer in comparison with ordinary pavement construction.

(3) The PERS structure is applied to the asphalt pavement, which can decrease the tensile stress at the foot of the surface layer and enhance driving comfort. It can be used in various structural layers of highways.

It is suggested that further studies should be concentrated on the mechanical properties of interlayer interfaces and bonding techniques.

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