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RESEARCH ARTICLE

Structural dimension optimization and mechanical response analysis of fabricated honeycomb plastic pavement slab

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ABSTRACT Because of favorable mechanical properties, deformation resistance and being conducive to environmental protection, honeycomb fabricated plastic pavement slabs are highly recommended these years. At present, most studies focus on the performance of plastic materials, however, the dimension optimization of fabricated plastic pavement slab is rarely mentioned. In this paper, an optimized geometry of the honeycomb pavement slab was determined through finite element analysis. Mechanical response of honeycomb slabs with different internal dimensions and external dimensions were explored. Several dimension factors were taken into consideration including the side length, rib thickness, the thickness of both top and bottom slabs of honeycomb structure and the length, the width and the thickness of the fabricated plastic slab. The results showed that honeycomb pavement slab with 6 cm bottom slab, 12 cm top slab,18 cm side length and 6 cm rib thickness is recommended, additionally, an external dimension of 4 m × 4 m × 0.45 m is suggested. Then, the mechanical responses of this optimized fabricated plastic slab were further investigated. Significance of different influencing factors, including wheel load, elastic modulus of plastic material, base layer thickness, soil foundation modulus and base layer modulus were ranked.

KEYWORDS honeycomb structure, plastic pavement, dimension optimization, mechanical response, factor significance

1 Introduction

Plastic pollution has become a severe problem across the world, which has seriously threatened the earth's environment [1–4]. For instance, the extensive production and use of plastics in China even led to over 30 million tons of waste plastics per year recently [2,5]. Similar situation can be noticed in Europe that nearly 25 million tons of plastic waste were produced each year but only less than 30% of which were well recycled [6]. According to the United States Environmental Protection Agency (EPA), 35370 tons of plastic were generated in 2017 in the U.S. but only 8.4% of which was recycled [7]. It is not difficult to find that the recovery rate of waste plastics is relatively low all over the world, which will aggravate the plastic pollution and cause a huge waste of resource and energy [8].

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Recycling of waste plastics will effectively solve this problem and play a key role in environmental protection. There have been a great number of studies in recycling waste plastic in road engineering field [9–11]. Generally, two recycling methods were employed, using as modifiers to prepare plastic modified asphalt or replacing some amount of aggregates [12,13]. Researchers found that adopting waste plastic modified asphalt in construction would improve the asphalt and asphalt mixture performances to certain extent [14–16]. Vasudevan et al. [17,18] tried to make small-sized waste plastic particles uniformly distribute on the heated aggregate and experiments showed that aggregate has increased hardness and toughness after modification. However, the recycling rate by these two methods is not satisfactory, usually less than 20% of asphalt mixture could be replaced by the waste plastic. Therefore, the fabrication technology came into researchers mind for its highest recycling rate when constructing fabricated plastic pavement.

A wide application of fabricated pavement structures in the field of infrastructure construction can be found in the last few decades. Zhou et al. [19] used finite element method to analyze the mechanical response of hollow cell slab and grid cell slab models constructed by ABS plastic in photovoltaic pavement. Zha et al. [20] proposed a hollow slab three-layer unit structure for solar pavement, comprising of a transparent protective layer made by Polymethylmethacrylate (PMMA) and plastic unit slab. Some researches proved that the geometry of fabricated slab and the adhesion between fabricated slab and base layer will directly affect the performance of precast slab under different traffic conditions [21,22]. So, it is not hard to realize that the geometry of fabricated slabs correlates closely to their performance. The commonly used slab structural forms are honeycomb, arch, I-shaped and round. Compared with other structures, closed hexagonal equilateral honeycomb structure can bear the maximum load with the least materials. Therefore, the application prospect of honeycomb fabricated slab is better [23,24]. Nevertheless, the commonly used fabricated slabs have limitations on geometric dimensions to some extent at present, research about the geometry and dimension optimization of honeycomb fabricated slabs needs to be further conducted.

The objective of this research is to propose an optimized structure of honeycomb plastic pavement slab and to investigate its mechanical properties through finite element method. Because it is currently found to be a very common calculation method to study the structural response of pavement structures from macro scope [25–28]. Thus, the three-dimensional finite element model of the plastic pavement slab was established by ABAQUS software. And an optimized internal dimension of the honeycomb pavement slab was first determined by investigating its mechanical response under different internal dimensions, including side length, rib thickness and the thickness of both top and bottom slabs. Then, the effect of length, width and thickness of the slab on its mechanical responses were studied to further optimize the external dimension. Additionally, the mechanical response analysis under different loads and working conditions were also studied.

2 Finite element modelling

2.1 Modelling assumptions

In order to facilitate simulation research and improve calculation efficiency, the plastic pavement model was reasonably simplified as a multi-layer elastic system in mechanical response analysis. The specific assumptions are as follows.

(1) The gravity effect of the plastic pavement is considered to approach the real service state of the plastic pavement as much as possible.

(2) The plastic material of the plastic pavement structural layer is an isotropic elastomer.

(3) The thickness of the plastic pavement slab is much larger than the maximum deflection under loading.

(4) The contact between the pavement slab and the structural layer is assumed to be frictionless while the contact between the base layer and the soil foundation is set to be completely connected.

(5) The foundation adopts elastic half-space foundation. The foundation used finite size and was expanded by the base layer. Also, the bottom of the foundation is fully constrained but the sides are unconstrained.

2.2 Modelling parameters

The three-dimensional finite element model of fabricated plastic pavement structure is composed of plastic pavement slab, cement stabilized base layer and soil foundation from top to bottom as shown in Fig. 1.

The corresponding model material parameters are shown in Table 1. The fabricated plastic pavement material used in this study is polyamide 66 with 30% glass fiber (PA66-GF30%) for its excellent heat resistance, chemical resistance and strength.

The vehicle load was adopted the standard single axle double wheel load, and the tire pressure is 0.7 MPa. For structural safety considerations, on the basis of ensuring same equivalent area, the single-axle double-wheel load is replaced with a single-axle single wheel and being placed at the unfavorable loading position, referring to the middle of longitudinal joint and the slab corner, as shown in Fig. 2.

The three-dimensional finite element model of the plastic pavement slab was established by ABAQUS software. And it should be noted that the honeycomb structure pavement slab was adopted due to its good compressive and bending strength. The dimension of the

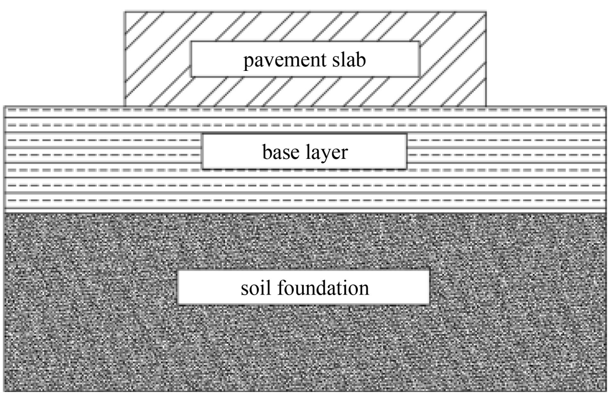

Fig. 1 Schematic diagram of plastic pavement structure model.

Table 1 Material parameters of pavement structure layer

structural layer	material	thickness (cm)	elastic modulus (MPa)	Poisson’s ratio
surface course	PA66-GF30% plastic	45	3000	0.3
base layer	cement stabilized macadam	20	1500	0.25
soil foundation	—	600	50	0.4

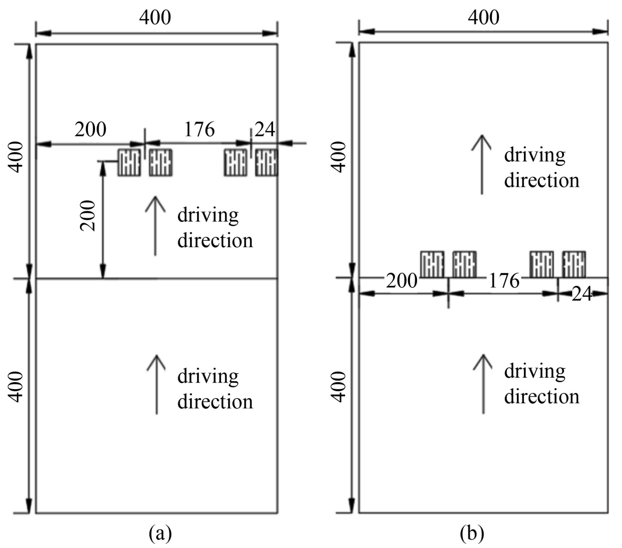

Fig. 2 Loading acting position (unit: mm): (a) middle of longitudinal joint; (b) slab corner.

whole pavement slab is 4 m × 4 m × 0.4 m. In the modeling, the size of plastic pavement slab is 2 m × 2 m. The default thickness of the foundation and the base layer are 6 and 0.2 m, respectively, and the different internal dimensions of the honeycomb structure pavement slab are shown in Fig.3.

3 Geometric dimension optimization of honeycomb structure pavement slab

3.1 Internal dimension optimization

Four different dimension factors including bottom slab thickness, top slab thickness, honeycomb side length and honeycomb rib thickness were adopted to investigate their effect on the maximum tensile stress, maximum compressive stress, vertical displacement and overall elastic modulus of the whole pavement slab. Therefore, the orthogonal test of four factors with four levels was designed, as shown in Table 2.

3.1.1 Effect of geometric dimensions of honeycomb structure on mechanical properties

The influence of geometric dimensions on various mechanical properties of honeycomb structure is presented in Fig. 4. K1, K2, K3, K4, respectively represented the average value of the tensile stress, compressive stress, vertical displacement and pavement slab modulus of the whole pavement slab simulated by the geometric dimension parameters of each pavement slab at four levels.

Figure 4(a) shows that the effect of bottom slab thickness on the maximum tensile stress of honeycomb structure is not obvious while that of other three dimension factors are noticeable and the most significant one is the top slab thickness. With the increase of the top slab thickness, the bending capacity is greatly strengthened, and the deformation under the same load is small, so that the tensile stress decreases correspondingly. From Fig. 4(b), it could be noticed that the effect of honeycomb rib thickness and top slab thickness on the maximum compressive stress is obvious. It could be explained by the better distribution of the load when these two thicknesses increased, Similarly, the effect of honeycomb rib thickness and top slab thickness on the vertical thickness is also significant as could be seen from

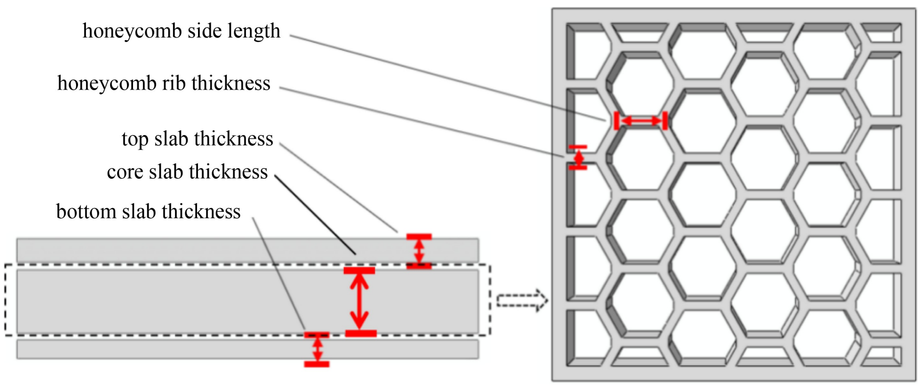

Fig. 3 Schematic diagram of the honeycomb structure pavement slab.

Fig. 4(c). The vertical displacement decreased dramatically because of the better distribution of stress when these two thicknesses increased. In addition, elastic modulus of pavement slab would be greatly influenced by the rib thickness of honeycomb structure as shown in Fig. 4(d). Thus, rib thickness is considered as the critical factor affecting the structural strength of pavement slab. In short, top slab thickness and rib thickness are considered as the critical dimension factor to mechanical properties of the honeycomb structure.

3.1.2 Linear regression analysis of mechanical response

To further relate the dimension of honeycomb structure to the mechanical responses of pavement slab, regression analyses were performed by quantifying the relationship between critical dimension factors, including bottom slab thickness (X_1), top slab thickness (X_2), honeycomb side length (X_3) and honeycomb rib thickness (X_4), and mechanical properties such as pavement slab tensile stress (Y_{ts}), compressive stress (Y_{cs}), vertical displacement (Y_{vd}) and slab elastic modulus (Y_m). SPSS statistics software was used to construct the multiple linear regression equation models. The established models are shown from Eqs. (1)–(4).

Table 2 Experimental factors and levels

factor level	bottom slab thickness (cm)	top slab thickness (cm)	honeycomb side length (cm)	honeycomb rib thickness (cm)
1	6	8	14	2
2	8	10	18	4
3	10	12	22	6
4	12	14	26	8

$$Y_{ts} = 1.579 + 0.006X_1 - 0.131X_2 + 0.060X_3 - 0.062X_4, \quad R^2 = 0.886, \tag{1}$$

$$Y_{cs} = 3.532 - 0.037X_1 - 0.119X_2 - 0.008X_3 - 0.102X_4, \quad R^2 = 0.731, \tag{2}$$

$$Y_{vd} = 0.831 - 0.001X_1 + 0.035X_2 + 0.014X_3 - 0.030X_4, \quad R^2 = 0.948, \tag{3}$$

$$Y_m = 556.512 + 15.613X_1 + 27.813X_2 - 34.038X_3 + 156.288X_4, \quad R^2 = 0.978. \tag{4}$$

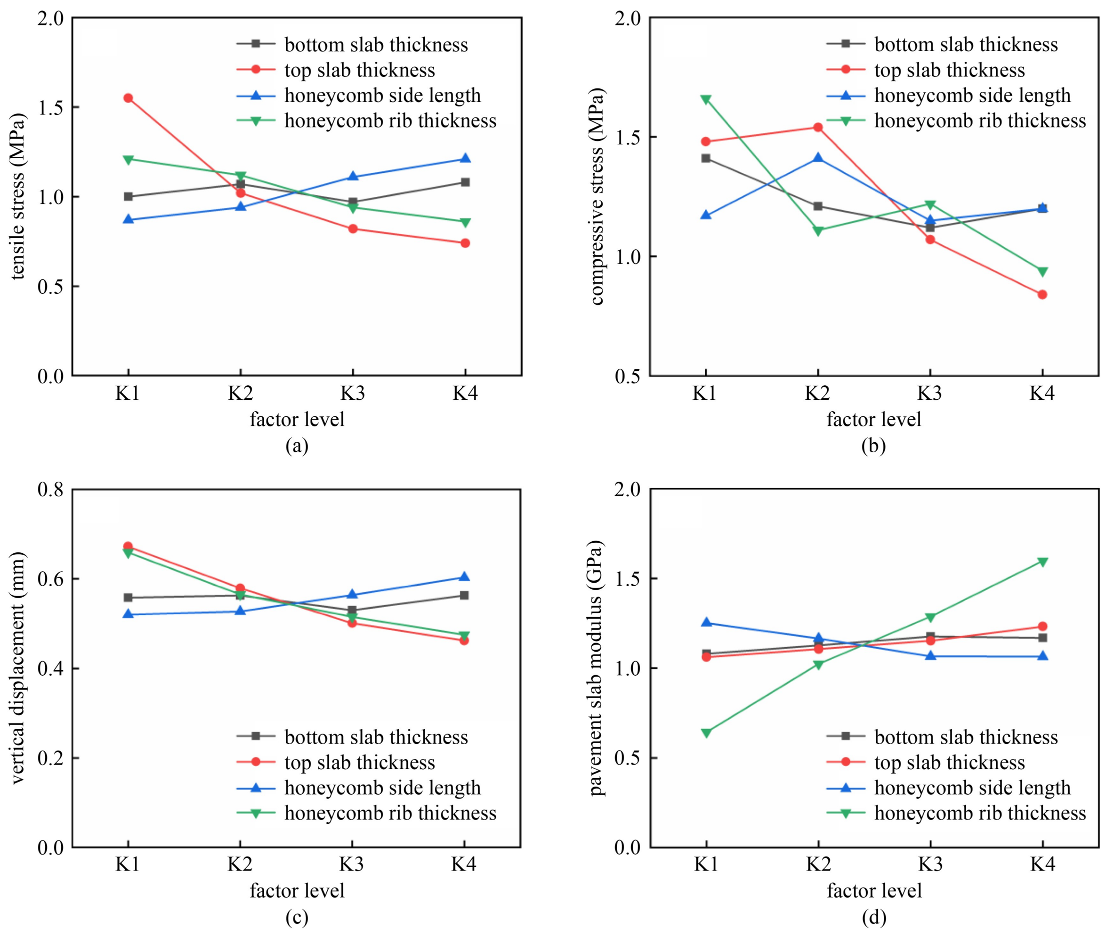

Fig. 4 Influence of geometric dimensions on: (a) maximum tensile stress; (b) maximum compressive stress; (c) vertical displacement; (d) pavement slab elastic modulus of honeycomb structure.

Equations (1)–(3) indicate that the top slab thickness of honeycomb structure contributes more to the mechanical performances of pavement slab except for the elastic modulus, which is greatly effected by the rib thickness of honeycomb as indicated by Eq. (4). This conclusion agrees with the results shown in Fig. 4.

Significance test was further conducted on these models and the results are shown in Table 3. The inspection level was set as 0.005 in this analysis, and it could be seen from Table 3 that the significance values of four models are lower than 0.005, verifying the rationality of these models.

3.1.3 Sensitivity analysis

The sensitivity index of evaluation index to the dimension change of whole pavement slab is proposed to assist geometric dimensions optimization, and the calculation formula is shown in Eq. (5).

$$S = \frac{I_{\max} - I_{\min}}{\bar{I}}, \tag{5}$$

where S is the sensitivity of the evaluation index to geometric dimensions changes, $I_{\max}$ is the maximum value of the evaluation index, $I_{\min}$ is the minimum value of the evaluation index, $\bar{I}$ is the average value of the evaluation index.

(1) Thickness of bottom slab

It could be found from Table 4 and Fig. 5 that the maximum tensile stress, vertical displacement and elastic modulus of the pavement slab are not sensitive to the variation of the bottom slab thickness, except for an obvious drop of maximum compressive stress when the bottom slab thickness increases from 6 to 8 cm. Therefore, considering the construction cost, the thickness of bottom slab is finally selected as 6 cm.

(2) Thickness of top slab

It could be observed from Table 4 and Fig. 6 that the maximum tensile stress and the maximum compressive stress of pavement slab noticeably change with the top slab thickness, especially from 8 to 12 cm. The tensile stress value decreases gradually while the compressive stress increases first but decreases then. Therefore, the top slab thickness of the pavement slab is selected as 12 cm.

(3) Honeycomb side length

It could be seen from Table 4 and Fig. 7 that the honeycomb side length has remarkable influence on the maximum tensile stress and the maximum compressive stress of pavement slab. When it increases from 16 to 22 cm, the change of maximum tensile stress is obviously greater than that of elastic modulus. When the honeycomb side length increases by 18 cm, the increase of vertical displacement is almost negligible. So that the honeycomb side length of pavement slab is selected as 18 cm.

Table 3 Significance F test of the model

model	sources of variation	sum of squares	degree of freedom	mean square	F value	Significance
1	regression	1.956	4	0.489	21.47	0
	residual	0.251	11	0.023		
	total	2.206	15			
2	regression	2.083	4	0.521	7.442	0.004
	residual	0.77	11	0.07		
	total	2.853	15			
3	regression	0.189	4	0.047	50.402	0
	residual	0.01	11	0.001		
	total	0.2	15			
4	regression	2.128E+06	4	5.320E+05	120.598	0
	residual	4.853E+04	11	4.412E+03		
	total	2.177E+06	15			

Table 4 Sensitivity of each evaluation index to internal dimensions

evaluation index	tensile stress	compressive stress	vertical displacement	elastic modulus
sensitivity (bottom slab thickness)	0.1	0.24	0.06	0.08
sensitivity (top slab thickness)	0.78	0.57	0.38	0.15
sensitivity (honeycomb side length)	0.33	0.21	0.15	0.16
sensitivity (honeycomb rib thickness)	0.34	0.58	0.33	0.84

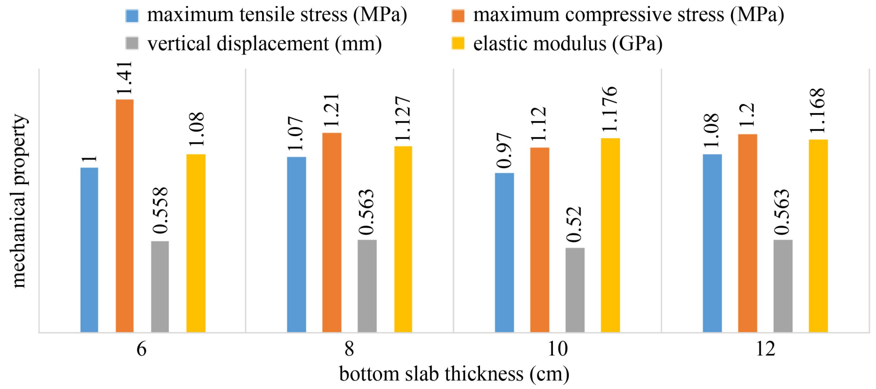

Fig. 5 Mechanical properties of plastic pavement slabs under different bottom slab thickness.

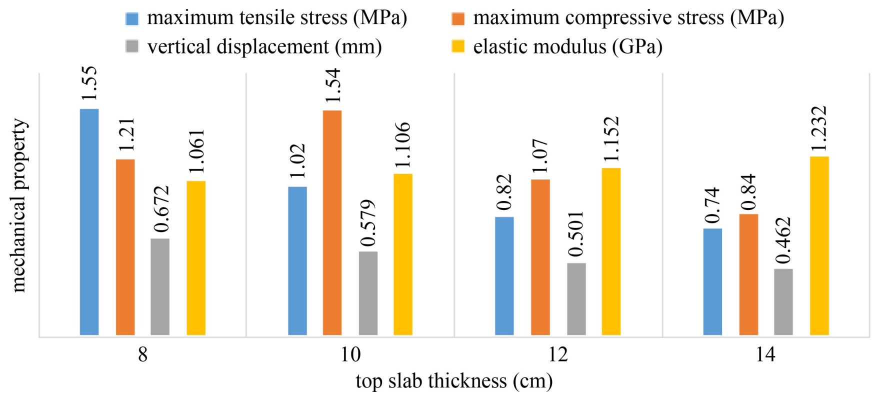

Fig. 6 Mechanical properties of plastic pavement slabs under different top slab thickness.

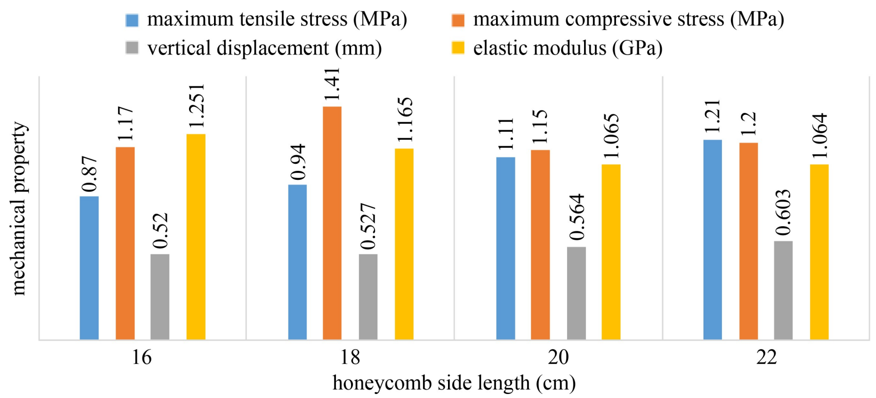

Fig. 7 Mechanical properties of plastic pavement slabs under different honeycomb side length.

(4) Honeycomb rib thickness

Table 4 and Fig. 8 illustrate that the elastic modulus is very sensitive to the change of the thickness of the honeycomb rib, and has a linear relationship with the thickness. When the thickness of the rib increases from 2 to 8 cm, the change of elastic modulus is very significant, because the thickness of the rib directly determines the overall bearing capacity and stability of the entire pavement slab. When the rib thickness continues to increase, the increased amplitude of each index value becomes smaller. Therefore, from the mechanical properties and economy viewpoint, the thickness of honeycomb rib is selected as 6 cm.

3.2 External dimension optimization of honeycomb plastic pavement slab

Similar to the size effect principle for concrete, the greater the size of concrete structure, the more the defects may appear in the structure and thus cause the degradation of mechanical properties. The honeycomb structures in plastic pavement slab can be taken as defects comparing with the solid pavement. Therefore, size effect principle may also be applicable to the plastic pavement slab and external dimension of honeycomb structure needs further optimization, in respect of its plain view size and thickness, by its mechanical responses.

3.2.1 Effect of plain view size of plastic pavement slab on mechanical responses

Overall dimension of honeycomb structure correlates closely with the mechanical properties of plastic pavement slab. Thus, the effect of plain view size of honeycomb structure on its maximum tensile stress and vertical displacement was explored to further optimize its dimension. The thickness of the whole structure is set as 40 cm. Ten honeycomb structure models with different plain view sizes were built as shown in Fig. 9.

Figure 10 showed the maximum tensile stress and vertical displacement of established models under longitudinal joint middle loading and corner loading. It could be found from Fig. 10(a) that the maximum tensile stress of the pavement slab appears on the bottom slab under longitudinal joint middle loading and it increased first to the peak value at the size of 2 m × 3 m and then decreased to a relative stable state. In addition, the maximum tensile stress on core slab was found to increase and even exceeded that of the top slab. And this could be explained by the shift of neutral surface of the pavement slab. However, the maximum tensile stress of the pavement slab appears on the top slab under corner loading as shown by Fig. 10(b). And with size increased, the tensile stress difference of the core slab and bottom slab gradually decreased. Furthermore, it could be noted from Fig. 10(c) that the effect of plain view size on vertical displacement is not obvious regardless of the loading position and they both have decreasing trend with slight fluctuations in general.

Generally, the variation trend of the maximum tensile stress of pavement slab with various size was complex due to the complication of honeycomb structure. As the dimensions of honeycomb structure plastic pavement slab increases, the maximum tensile stress increases at first, then decreases, and finally tends to be stable, while the vertical displacement presents a slight downtrend. So, model 6 with 4 m × 4 m is finally adopted according to the mechanical responses of the slab and referenced the size of cement pavement slab as well.

3.2.2 Effect of plastic pavement slab thickness on mechanical responses

Not only the plain view size of honeycomb structure, but

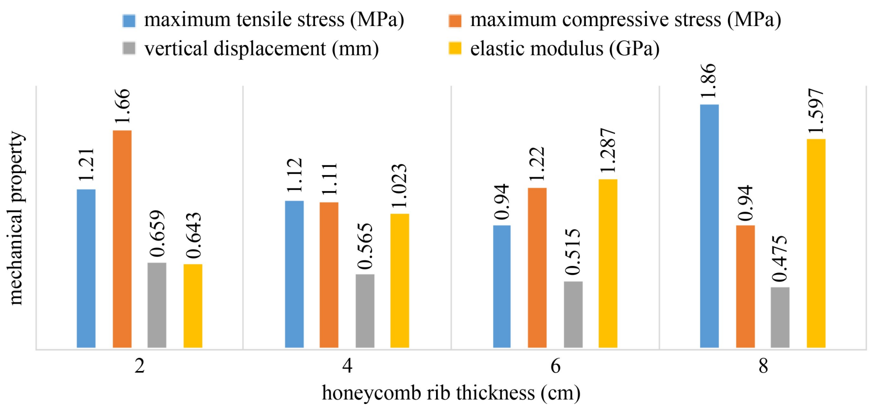

Fig. 8 Mechanical properties of plastic pavement slabs under different honeycomb rib thickness.

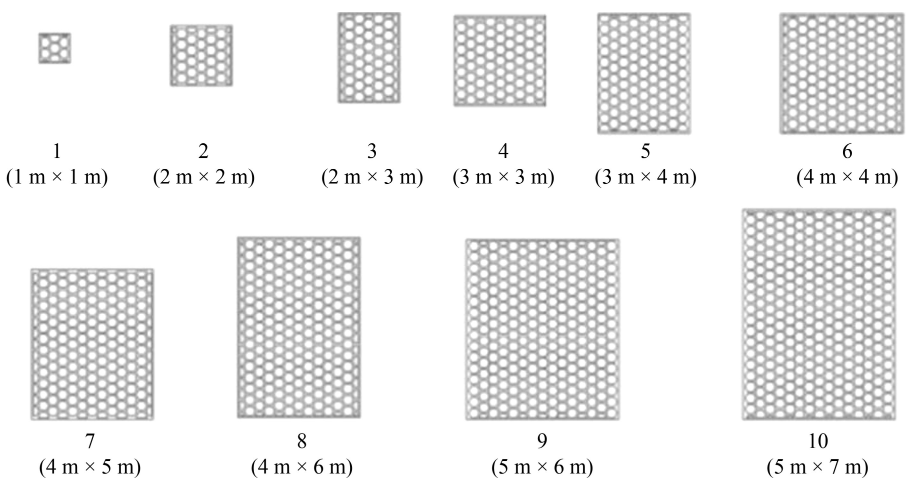

Fig. 9 Dimension model of plastic pavement slab.

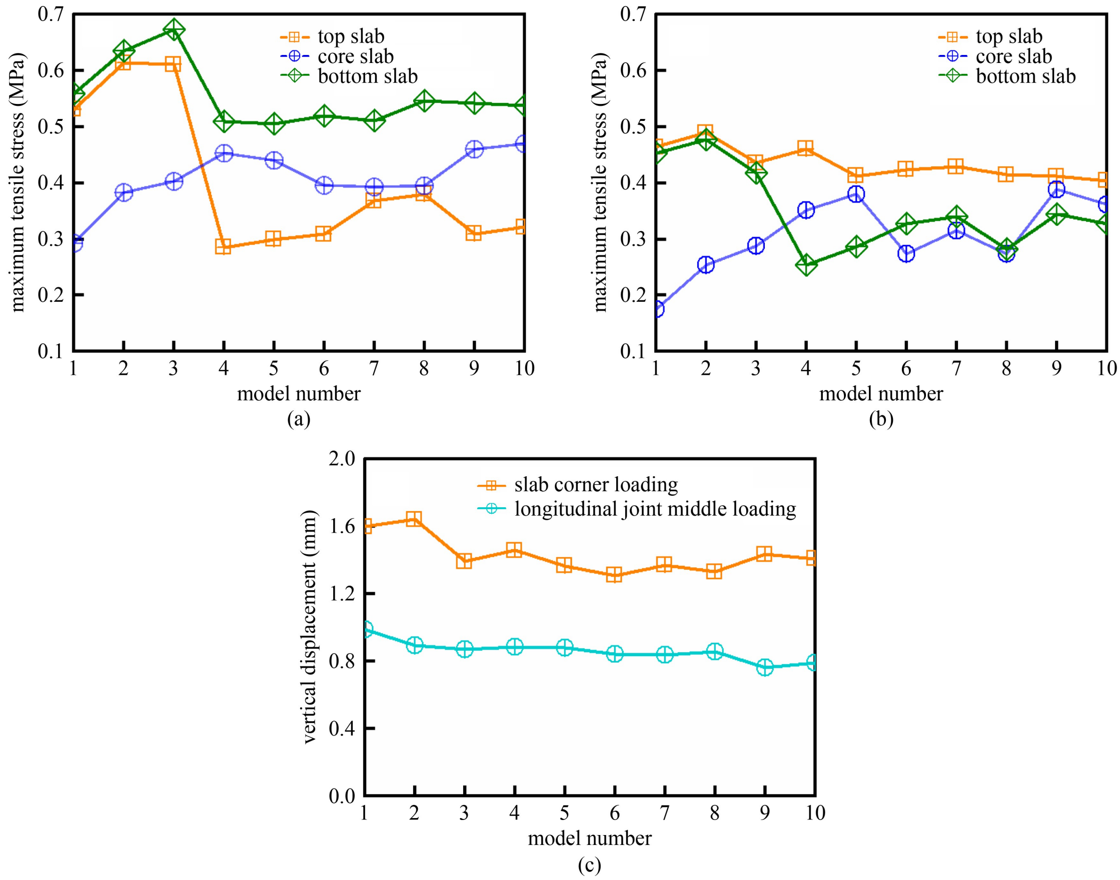

Fig. 10 Maximum tensile stress: (a) under longitudinal joint middle loading; (b) under corner loading; and (c) vertical displacement of the honeycomb structure with different plain view size.

also the thickness of that correlates closely with the mechanical properties of plastic pavement slab. Thus, the effect of thickness of honeycomb structure on its maximum tensile stress and vertical displacement was explored to further optimize its dimension. It should be noted that variation of honeycomb structure thickness is caused by the changing of core slab thickness because that of top and bottom slabs have been determined as 12 and 6 cm respectively. As can be seen from Fig. 11(a), it is found that the maximum tensile stress of the core slab and bottom slab decreased with the increasing of thickness while that of top slab remains stable except an obvious drop was noted when thickness changed from 20 to 25 cm. Thus, the effect of plastic slab thickness only has limited effect on the maximum tensile stress of top slab. Similar situation could be observed from Fig. 11(b). However, it could be found that the critical load position was on the bottom slab under longitudinal joint middle loading rather than the top slab under corner loading. As shown in Fig. 11(c), the vertical displacement decreased with the increase of the plastic pavement slab and this trend was not that obvious after a certain value of thickness. Therefore, the thickness of plastic pavement slab is taken 45 cm.

Shortly, the above results suggest that honeycomb structure with 18 cm side length, 6 cm thickness, 6 cm bottom slab and 12 cm top slab is recommended, and an optimized dimension of 4 m × 4 m × 0.45 m is suggested.

4 Mechanical response analysis of the optimized honeycomb plastic pavement slab

The applicable situation of the optimized honeycomb plastic pavement slab was further determined through its mechanical responses under different loads, plastic modulus, soil modulus, base layer modulus and thickness. And the plastic pavement slab model is constructed as shown in Fig. 1.

4.1 Effect of wheel load

As can be seen from Fig. 12, the maximum tensile stress and vertical displacement of honeycomb plastic pavement slab increase linearly with the increase of load, and the difference of maximum tensile stress and vertical displacement at the slab corner and the middle of longitudinal joint increases gradually. It is obvious form Fig. 12 that the mechanical response of plastic pavement is sensitive to the load variation. Although the maximum

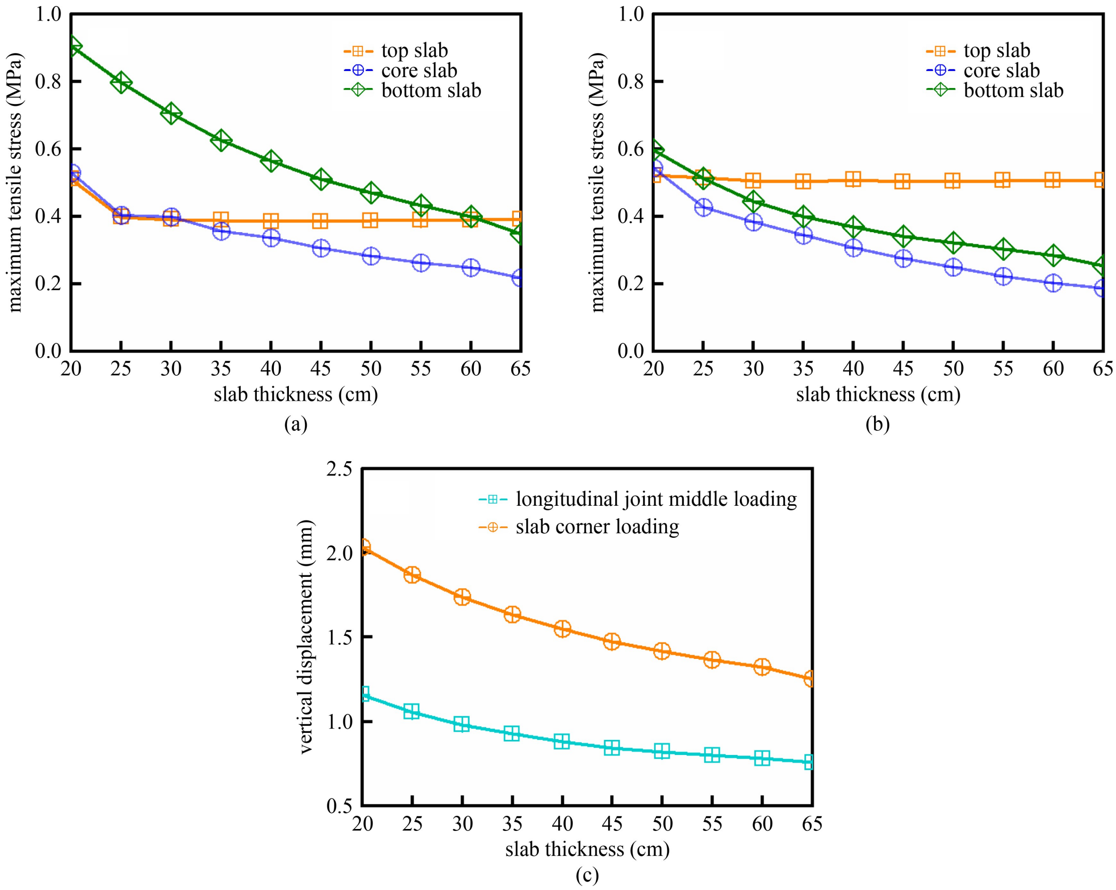

Fig. 11 Maximum tensile stress: (a) under longitudinal joint middle loading; (b) under corner loading; and (c) vertical displacement of the honeycomb structure with different slab thickness.

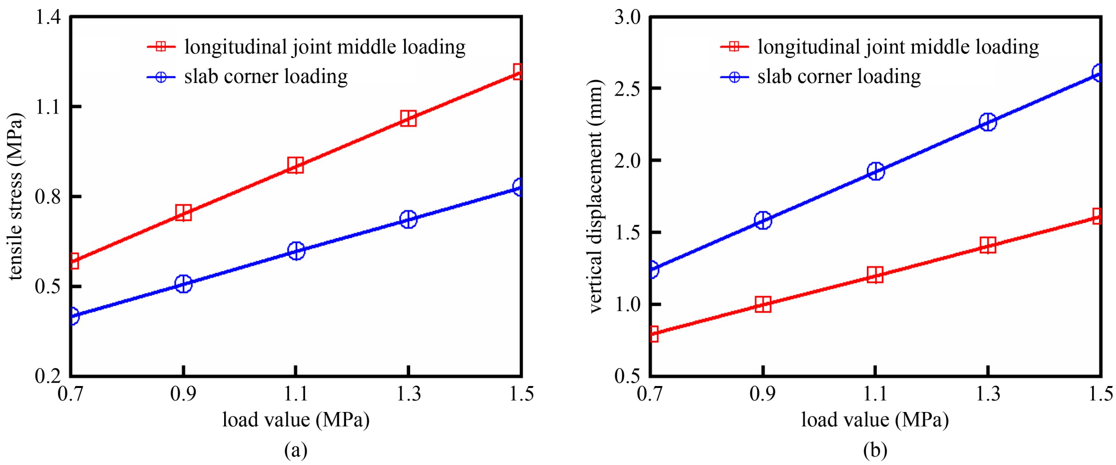

Fig. 12 Mechanical response of plastic pavement under different loads: (a) maximum tensile stress; (b) vertical displacement.

tensile stress increases greatly with the increasing load, it is still far less than the limit tensile strength of PA66-GF 30% plastic, ensuring the structural safety of pavement slab. However, it should be cautious about the maximum vertical displacement for it exceeds 2.5 mm and is much higher than that of traditional asphalt pavement. Therefore, the honeycomb plastic pavement slab is not suitable to be used in some excessive heavy-load areas, such as mining area and heavy industrial district.

4.2 Effect of elastic modulus of plastic material

As shown in Fig. 13(a), the maximum tensile stress of pavement slab increased with the elastic modulus of plastic material, which is attributed to the increase of tensile stress caused by the deformation. In addition, the slope of the curves in Fig. 13(a) decreased, indicating that the effect of elastic modulus of plastic materials on the maximum tensile stress of pavement slab becomes insignificant gradually.

As can be seen from Fig. 13(b), the vertical displacement of pavement slab decreases with the increase of the elastic modulus of plastic material as expected. Because plastic material with higher elastic modulus will show better resistance to deformation. Thus, the vertical displacement of plastic pavement can be reduced by increasing the elastic modulus of plastic material, and the maximum tensile stress will not exceed the tensile strength of the material.

4.3 Effect of base layer thickness

As can be seen from Fig. 14(a), with the increase of base layer thickness, the maximum tensile stress in the middle of longitudinal joint of pavement slab slightly increases at first then decreases. Whereas the maximum tensile stress at slab corner decreases at first then increases. Additionally, as shown in Fig. 14(b), generally the vertical displacement under the middle longitudinal loading and slab corner loading shows a decreasing trend except a sharp increase at the base layer thickness of 24 cm. With the increasing of the base layer thickness, the critical position of the maximum tensile stress on pavement slab changes from the middle of longitudinal joint to the slab corner. This is owing to the decrease of deformation on the middle of longitudinal joint caused by the increased strength when the base layer thickness is greater. But due to the changing of neutral surface under slab corner loading, the tensile stress shows an increasing trend.

4.4 Effect of base layer modulus

As shown by Fig. 15, the tensile stress and vertical displacement of pavement slab does not change with the modulus of base course, thus, the effect of base layer modulus on the mechanical responses of pavement slab is negligible regardless of the loading position.

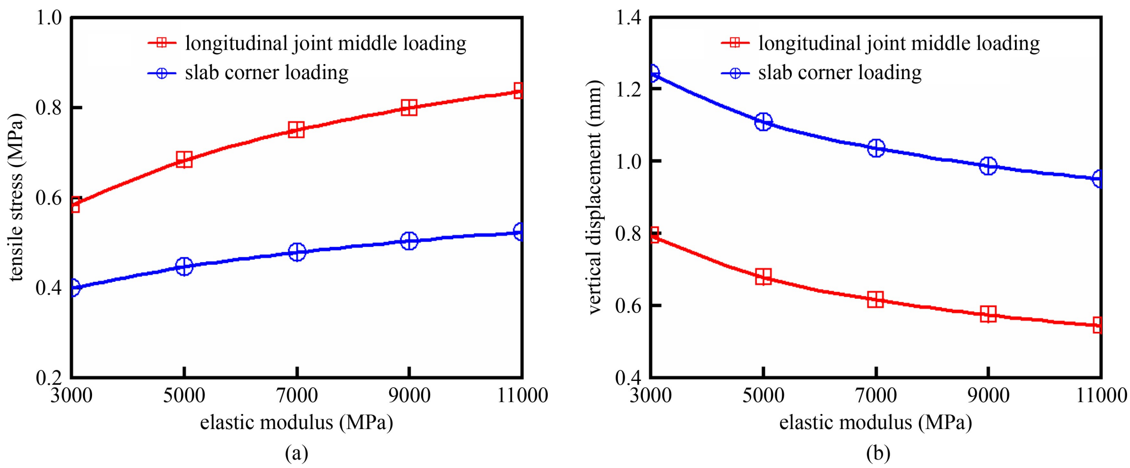

Fig. 13 Mechanical response of plastic pavement under different plastic material modulus: (a) maximum tensile stress; (b) vertical displacement.

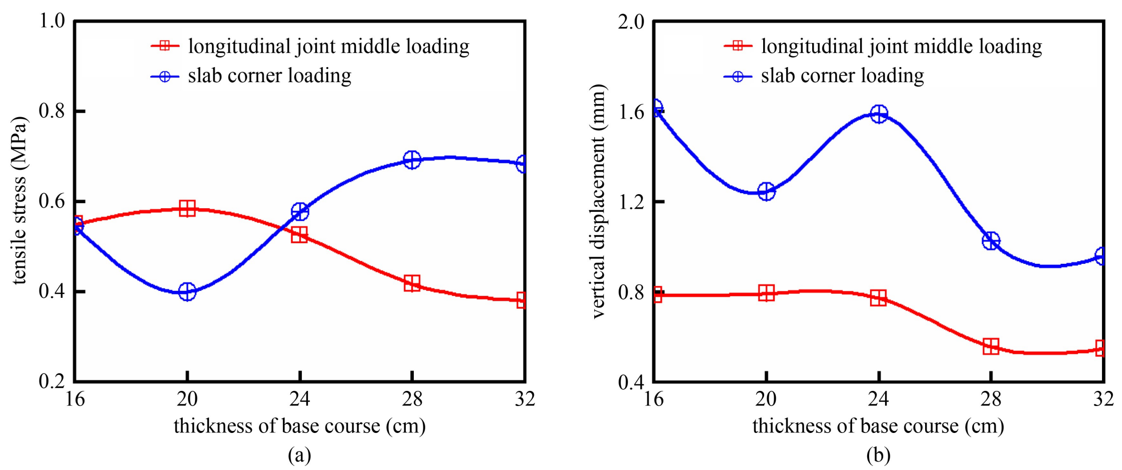

Fig. 14 Mechanical response of plastic pavement under different base layer thickness: (a) maximum tensile stress; (b) vertical displacement.

4.5 Effect of soil foundation modulus

Figure 16(a) shows that the maximum tensile stress in the middle of longitudinal joint and at the slab corner decrease with the soil foundation modulus increasing, and this could be owing to the increase of support under pavement slab when the soil foundation modulus increases. Similar trend can be found in Fig. 16(b) for the vertical displacement. When the soil foundation modulus increases from 30 to 90 MPa, the vertical displacement decreases by 0.564 and 0.951 mm respectively in the middle of longitudinal joint and at the corner of slab. Therefore, it can be concluded that the soil foundation modulus has a great influence on the vertical displacement of the whole pavement slab.

4.6 Sensitivity analysis of influencing factors of mechanical response

Sensitivity analysis was made on mechanical responses, including the tensile stress and the vertical displacement, in terms of five different influencing factors mentioned above. The combination of box plots and variance diagram is used to present the significant influence degree of each factor on the mechanical response of plastic pavement structure. Box plots reflect the distribution characteristics of original data, including extreme value, mean value, median value and upper and lower quartiles, while variance reflects the dispersion degree of multiple data. Results are shown in Fig. 17 and it can be noticed from Fig. 17(a) that influencing degree of factors on tensile stress from significant to negligible are sequenced as the wheel load, elastic modulus of plastic material, thickness of base layer, soil modulus and base layer modulus. The influence of vehicle load on tensile stress is obviously greater than other factors. Moreover, the influence of vehicle load on tensile stress is approximately linear obtained from the vehicle load box plot, so plastic pavement is not suitable for roads in heavy-duty areas. Elastic modulus of plastic material, base layer thickness and soil foundation modulus have

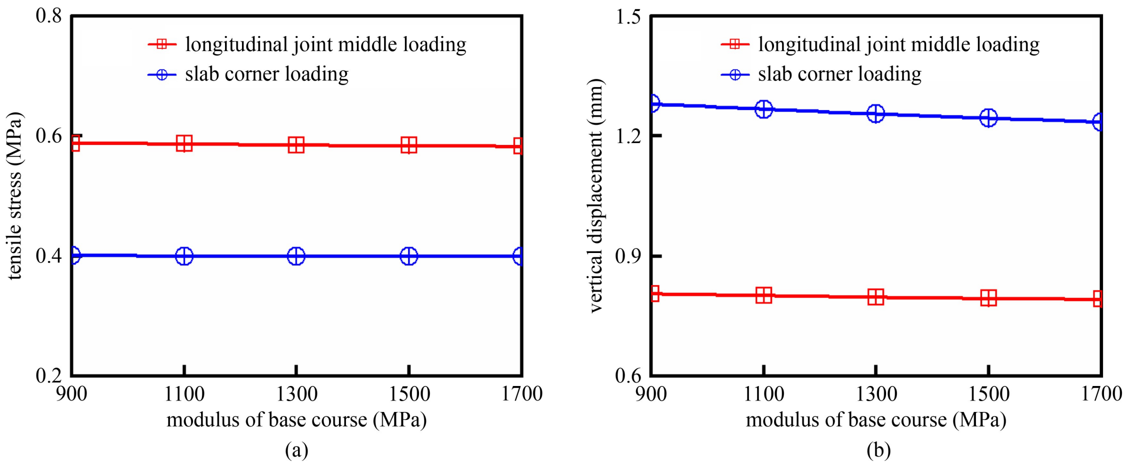

Fig. 15 Mechanical response of plastic pavement under different base layer modulus: (a) maximum tensile stress; (b) vertical displacement.

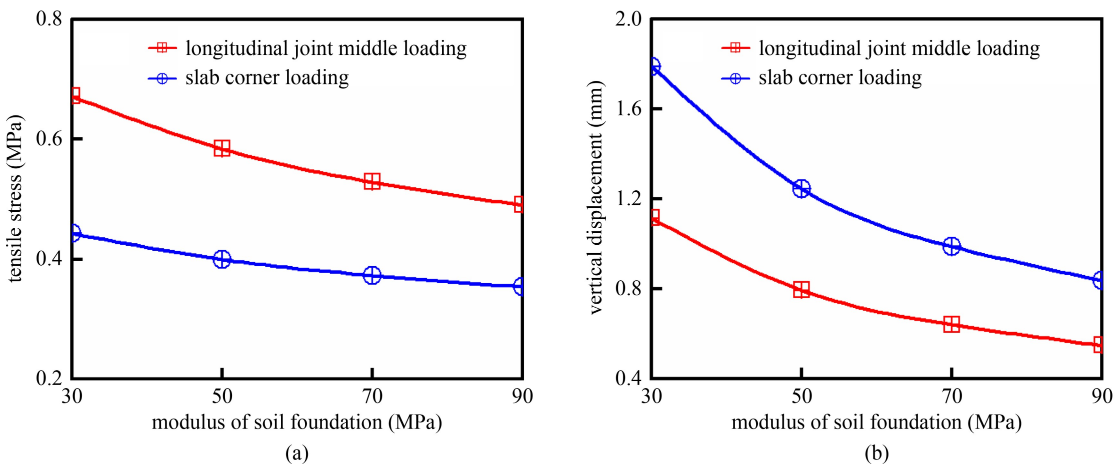

Fig. 16 Mechanical response of plastic pavement under different soil foundation modulus: (a) maximum tensile stress; (b) vertical displacement.

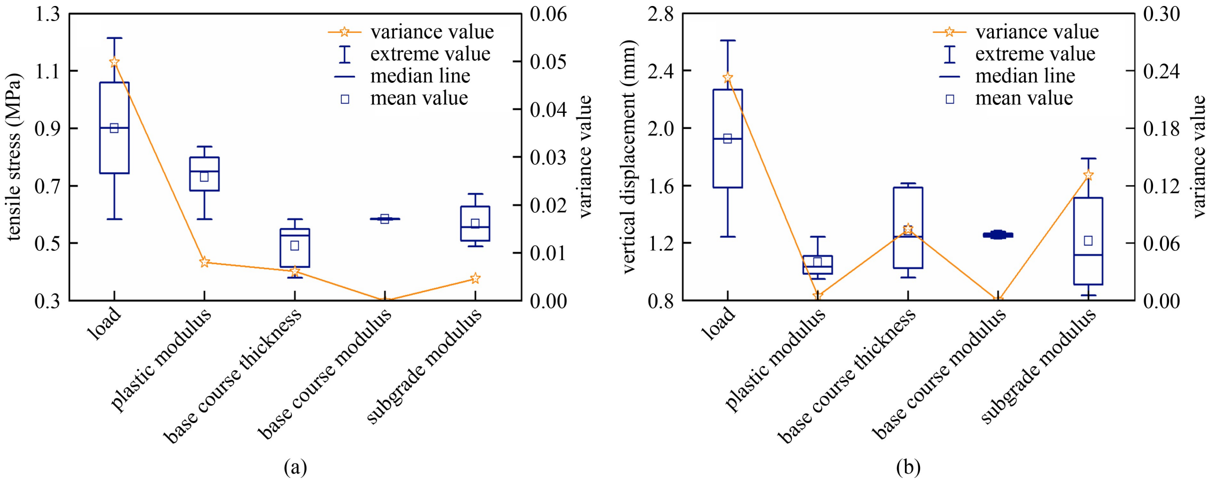

Fig. 17 Influence degree of various factors on: (a) tensile stress; (b) vertical displacement.

similar influence degree on tensile stress, and the base layer modulus has almost no effect.

As shown in Fig. 17(b), influencing degree of factors on vertical displacement from significant to negligible are sequenced as the wheel load, soil modulus, thickness of base layer, elastic modulus of plastic material and base layer modulus. Similar to the results of tensile stress, wheel load is the most significant influencing factor while the base layer modulus is the negligible one. Increasing wheel load will cause larger vertical displacement of plastic pavement, and serious deformation of pavement slab will also do harm to its durability. Therefore, controlling the wheel load and increasing base layer thickness is an effective way to reduce tensile stress and vertical displacement of plastic pavement under loading.

5 Conclusions

This study proposed an optimized dimension of honeycomb fabricated plastic pavement slab in terms of mechanical responses through the results of orthogonal tests, linear regression analysis and sensitivity analysis, and the conclusions are drawn as follows.

1) For the internal dimension of honeycomb structure, top slab thickness and rib thickness are considered as two critical dimension factor in regard to its mechanical properties. In addition, top slab thickness is of most significant to the tensile stress, compressive stress and vertical displacement while rib thickness will greatly determine the elastic modulus of honeycomb structure.

2) The optimized internal dimension of honeycomb structure is 6 cm bottom slab thickness, 12 cm top slab thickness, 18 cm honeycomb side length and 6 cm honeycomb rib thickness and the optimized external dimension of fabricated plastic pavement slab is 4 m × 4 m × 0.45 m.

3) For the mechanical responses of honeycomb plastic pavement slab with different external dimension, the vertical displacement decreases with the increase of slab thickness and gradually becomes stable when it comes to a certain extent. Meanwhile, the maximum tensile stress shows up at different position according to different plain view size of slab, shifting from the core slab to the bottom slab with the increase of plain view size.

4) The significance of various factors with respect to mechanical responses of optimized honeycomb plastic pavement slab is sequenced as:

(i) for tensile stress: wheel load > elastic modulus of plastic material > base layer thickness > soil modulus > base layer modulus;

(ii) for the vertical displacement: wheel load > soil modulus > base layer thickness > elastic modulus of plastic material > base layer modulus.

Additionally, the honeycomb plastic pavement slab is not suggested to be used in some excessive heavy-load areas.

5) The results have indicated that the optimized honeycomb plastic pavement slab proposed in this study satisfies the requirement of the mechanical properties.

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References

1. Heacock M, Kelly C B, Asante K A, Birnbaum L S, Bergman Å L, Bruné M N, Buka I, Carpenter D O, Chen A, Huo X, Kamel M, Landrigan P J, Magalini F, Diaz-Barriga F, Neira M, Omar M, Pascale A, Ruchirawat M, Sly L, Sly P D, Van den Berg M, Suk W A. E-waste and harm to vulnerable populations: A growing global problem. Environmental Health Perspectives, 2016, 124(5): 550–555

2. Wang W, Themelis N J, Sun K, Bourtsalas A C, Huang Q, Zhang Y, Wu Z. Current influence of China’s ban on plastic waste imports. Waste Disposal and Sustainable Energy, 2019, 1(1): 67−78
3. Van Sebille E, Spathi C, Gilbert A. The ocean plastic pollution challenge: Towards solutions in the UK. Grantham Institute Briefing paper, 2016, 19(02): 1−16
4. Chen S, Zhang Y, Guo C, Zhong Y, Wang K, Wang H. Separation of polyvinyl chloride from waste plastic mixtures by froth flotation after surface modification with sodium persulfate. Journal of Cleaner Production, 2019, 218: 167−172
5. Zhou H, Long Y, Meng A, Li Q H, Zhang Y G. Thermogravimetric characteristics of typical municipal solid waste fractions during co-pyrolysis. Waste Management (New York, N.Y.), 2015, 38(5): 194−200
6. Leal Filho W, Saari U, Fedoruk M, Iital A, Moora H, Klöga M, Voronova V. An overview of the problems posed by plastic products and the role of extended producer responsibility in Europe. Journal of Cleaner Production, 2019, 214: 550−558
7. He P, Chen L, Shao L, Zhang H, Lü F. Solid waste (MSW) landfill: A source of microplastics? Evidence of microplastics in landfill leachate. Water Research, 2019, 159: 38−45
8. Khoo H H. LCA of plastic waste recovery into recycled materials, energy and fuels in Singapore. Resources, Conservation and Recycling, 2019, 145: 67−77
9. Duggal P, Shisodia A S, Havelia S, Jolly K. Use of waste plastic in wearing course of flexible pavement. Advances in Structural Engineering and Rehabilitation, 2020, 38: 177−187
10. Chin C, Damen P. Viability of using recycled plastics in asphalt and sprayed sealing applications. Sydney, Australia, Austroads Publication. No. AP-T351–19, 2019
11. Sw A, Lm B. Repurposing waste plastics into cleaner asphalt pavement materials: A critical literature review. Journal of Cleaner Production, 2021, 280: 124355
12. Gautam P K, Kalla P, Jethoo A S, Agrawal R, Singh H. Sustainable use of waste in flexible pavement: A review. Construction & Building Materials, 2018, 180(2): 239−253
13. Bansal S, Kumar Misra A, Bajpai P. Evaluation of modified bituminous concrete mix developed using rubber and plastic waste materials. International Journal of Sustainable Built Environment, 2017, 6(2): 442−448
14. Al-Hadidy A, Tan Y. Effect of polyethylene on life of flexible pavements. Construction & Building Materials, 2009, 23(3): 1456−1464
15. Behl A, Sharma G, Kumar G. A sustainable approach: Utilization of waste PVC in asphalting of roads. Construction & Building Materials, 2014, 54(4): 113−117
16. Haider S, Hafeez I, Jamal, Ullah R. Sustainable use of waste plastic modifiers to strengthen the adhesion properties of asphalt mixtures. Construction & Building Materials, 2020, 235(6): 117−496
17. Vasudevan R, Rajasekaran S, Saravanavel S. Reuse of waste plastics for road laying. Indian Highways (Indian Roads Congress), 2006, 34(7): 5−20
18. Vasudevan R, Ramalinga Chandra Sekar A, Sundarakannan B, Velkennedy R. A technique to dispose waste plastics in an ecofriendly way—Application in construction of flexible pavements. Construction & Building Materials, 2012, 28(1): 311−320
19. Zhou B, Pei J, Hughes B R, Nasir D S N M, Zhang J. Analysis of mechanical properties for two different structures of photovoltaic pavement unit block. Construction & Building Materials, 2020, 239(04): 117−864
20. Zha X, Zhang C, Wu Z, Zhang Q. Mechanical analysis and model preparation for hollow slab element of solar pavement. Acta Energiae Solaris Sinica, 2016, 37(2): 136–141 (in Chinese)
21. Ashtiani R S, Jackson C J, Saeed A, Hammons M I. Pre-Cast Concrete Panels for Contingency Rigid Airfield Pavement Damage Repairs. Panama City: Applied Research Associates Inc Panama City FL, 2010
22. Priddy L P, Jersey S R, Reese C M. Full-scale field testing for injected foam stabilization of Portland cement concrete repairs. Transportation Research Record: Journal of the Transportation Research Board, 2010, 2155(1): 24−33
23. Davalos J F, Qiao P, Frank Xu X, Robinson J, Barth K E. Modeling and characterization of fiber-reinforced plastic honeycomb sandwich panels for highway bridge applications. Composite Structures, 2001, 52(3−4): 441−452
24. Ryzhenkov A V, Lapin E E, Loginova N A, Sitdikov D R, Grigor’ev S V. Evaluation of the thermal efficiency of a high-temperature heat-insulation structure based on honeycomb plastic. Thermal Engineering, 2016, 63(6): 445−448
25. Zhang J, Fan Z, Wang H, Sun W, Pei J, Wang D. Prediction of dynamic modulus of asphalt mixture using micromechanical method with radial distribution functions. Materials and Structures, 2019, 52(2): 49
26. Lye L, Dong Y, Zhao D, Wen Y. Mechanical and acoustic properties composition design and effects analysis of poroelastic road surface (PERS). Journal of Materials in Civil Engineering, 2021, 33(10): 04021281
27. Zhang J, Tan H, Pei J, Qu T, Liu W. Evaluating crack resistance of asphalt mixture based on essential fracture energy and fracture toughness. International Journal of Geomechanics, 2019, 19(4): 06019005
28. Zhang Y, Ma T, Ling M, Huang X. Mechanistic sieve size classification of aggregate gradation by characterizing load carrying capacity of inner structures. Journal of Engineering Mechanics, 2019, 145(9): 04019069