Mechanical response analysis and optimization of snap on Prefabricated Concrete Pavement Slab

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Abstract: In this paper, a kind of assembled cement concrete pavement slab was numerical analysis to investigate the influence of the size of the tongue and groove joint on load transfer capacity between slabs and the maximum stress in the slab. And the load transfer capacity of the slab and the maximum stress in the panel of different sizes are optimized.

1. Introduction

The assembled cement pavement has the characteristics of short construction period, short maintenance time, environmental protection, construction not affected by climate, low cost and so on, so it has been more and more used in road engineering. However, in practical application, the development was restricted by the problem of poor integrity.

In recent years, domestic institutions have carried out a lot of research work on cement concrete joints. He Kaihan's team gives his views on prefabrication and assembly technology from five aspects: slab planning, pavement structure size layout, long-term performance requirements, materials used in each layer and construction technology[1]. Through numerical simulation, Tian Zhichang’s team studies and analyzes the stress characteristics of assembled cement concrete pavement slabs under different slab sizes, different joints, and the deflection transfer effect at joints, and puts forward an optimization scheme of slab structure according to the analysis results[2]. Sun Jiancheng's team studied the effects of edge length, thickness and elastic modulus of prefabricated slabs on the mechanical behavior of the bottom of the base by using finite element software and orthogonal test method[3]. Yan Qiulong's team used numerical analysis to analyze the stress and strain response of circular concrete pavement joints caused by the change of span ratio under standard axial load[4]. Feng Zhixuan's team made a mechanical analysis of the assembled asphalt pavement used in the extreme environment of desert[5]. However, the mechanical response analysis of pavement structure usually only considers the vertical load while neglecting the horizontal load. The vehicle will apply horizontal shear force along the driving direction to the road will be applied to the road surface during braking. Under the long-term action, the adjacent two slabs will produce relative displacement, which will greatly reduce the load transfer capacity of the tongue and groove joint and seriously destroy the integrity of the assembled pavement.In this paper, a new type of assembled cement concrete pavement slab is proposed, in which a pair of buckles are added to both sides of the original panel. On the one hand, the buckle is used to offset the horizontal shear force produced by the braking force of the vehicle to make the numerical simulation result close to the actual use condition. On the other hand, the buckle is used to limit the
relative displacement between the two adjacent slabs to improve the integrity of the assembled pavement. And then the Numerical analysis was adopted to analyze the stress-strain response of this new type of assembled cement concrete pavement slab. Finally, put forward some optimization suggestions.

2. Finite element modeling of the snap-on slab

2.1. Calculation parameters and Model Establishment

In this paper, the model is established by finite element software for numerical analysis. The mechanical model is a three-dimensional model composed of subgrade, base and surface layer, which is 3.5 m in length and 3.5 m in length and width. The specific materials and parameters of each structural layer are shown in table 2.1. The finite element model of pavement slab is shown in figure 2.1.

| structure layer | thickness/cm | modulus /Mpa | Poisson ratio |
|-----------------|--------------|--------------|--------------|
| Surface layer   | 24           | 30000        | 0.15         |
| base            | 60           | 1200         | 0.25         |
| Subgrade        | 700          | 40           | 0.30         |

![Table 2.1. Model parameters Table.](image)

Figure 2.1. Finite element model of Pavement Plate.

![Figure 2.2. Simplified diagram of wheel load (cm).](image)

Figure 2.2. Simplified diagram of wheel load (cm).

![Figure 2.3. Simplified diagram of load position.](image)
Because of the large modulus difference between the structural layers, the shear stress between the layers is large. If the indirect contact of the floor is set to be completely continuous, it is not only quite different from the actual situation, but also can not analyze the shear force between stories. Therefore, in this paper, the contact relationship between subgrade and base is set as contact non-separation, the contact condition between base and surface layer is set as contact non-separation, and Coulomb friction model is selected in tangential direction.

In this paper, \( P = 25 \) kN and \( p = 700 \) kPa for the standard axle load BZZ-100 specified in the current road surface design code are used, and the contact surface of one of the wheels and the road surface in the single-axis two-wheel group is idealized as a square surface of 20 cm to 20 cm. In practical use, most of the structural damage of cement concrete pavement occurs at the joint, so the assembled pavement joint is selected for loading analysis. The stress of the concave plate and the convex slab are basically the same, so only the load analysis is carried out on the convex slab side. The final load simplification diagram and load position diagram are shown in figure 2.2 and figure 2.3.

3. numerical simulation and analysis

3.1. Orthogonal test parameter selection

Orthogonal experimental design is a kind of design research method for multi-factor and multi-level. In order to simplify the experimental steps and reduce the number of experiments, the simulation results are analyzed by orthogonal analysis in this paper. The factors that affect the transmission efficiency of the tenon and groove joint (as shown in figure 3.1) are mainly three: the tenon length \( a \), the tenon thickness \( b \) and the tenon slope \( i \). In this paper, the orthogonal test is carried out by changing the tenon length \( a \), the tenon thickness \( b \) and the tenon slope \( i \), and the horizontal table of the orthogonal test factors is established, as shown in table 3.

![Figure 3.1. Schematic diagram of the structure of the tongue and groove joint.](image)

| parameter | A. Tenon length \( a \) (cm) | B. Tenon thickness \( b \) (cm) | C. Tenon slope \( i \) |
|-----------|-----------------|-----------------|-----------------|
| horizontal | 1               | 2               | 4               |
|           | 2               | 3               | 6               |
|           | 3               | 4               | 8               |

3.2. Orthogonal test design and results

Because the load transfer efficiency between slabs can not be measured accurately, the stress and displacement between the load slab and the non-load slab are generally used to characterize the load transfer capability between the load slab and the non-load slab. From the practical measurement effect, the deflection ratio can be measured more accurately than the strain ratio, which is easy to be accepted by people, and it is also more convenient to be applied to the calculation and analysis. Therefore, in general, the deflection ratio is used as the load transfer coefficient to characterize the load transfer capacity of the joint. So load transfer coefficient \( \eta = \omega_1/\omega_2 \times 100\% \), The \( \omega_2 \) in the formula indicates the deflection of the bottom edge of the load slab, the \( \omega_2 \) in the formula indicates the deflection of the bottom edge of the non-load slab. According to the orthogonal table \( L_6(3^4) \), 9 sets of representative
parameter combinations are selected, and then design the orthogonal test plan table. The results obtained by finite element software simulation are shown in table 3.2.

Table 3.2. Orthogonal design table.

| A: tenon Length (a cm) | B: tenon Thickness b (cm) | C: tenon slope i | Load transfer coefficient $\mu$ (%) | Maximum stress of convex plate MPa |
|-----------------------|--------------------------|-----------------|-----------------------------------|----------------------------------|
| 2                     | 4                        | 1: 2            | 97.55                             | 1.078                            |
| 2                     | 6                        | 1: 3            | 98.10                             | 1.045                            |
| 2                     | 8                        | 1: 4            | 98.20                             | 1.016                            |
| 3                     | 4                        | 1: 3            | 98.44                             | 1.193                            |
| 3                     | 6                        | 1: 4            | 98.80                             | 1.049                            |
| 3                     | 8                        | 1: 2            | 97.54                             | 0.772                            |
| 4                     | 4                        | 1: 4            | 99.13                             | 1.165                            |
| 4                     | 6                        | 1: 2            | 98.02                             | 0.847                            |
| 4                     | 8                        | 1: 3            | 98.58                             | 0.842                            |

3.3. Analysis of orthogonal test result

Table 3.3. Analysis of the results of the transmission coefficient.

| A | B | C |
|---|---|---|
| K1 | 97.95 | 98.37 | 97.7 |
| K2 | 98.26 | 98.31 | 98.37 |
| K3 | 98.58 | 98.11 | 98.71 |
| R  | 0.63 | 0.26  | 1.01 |

Table 3.4. Analysis table of maximum stress results of convex plates.

| A | B | C |
|---|---|---|
| K1 | 1.053 | 1.145 | 0.899 |
| K2 | 1.005 | 0.987 | 1.033 |
| K3 | 0.951 | 0.877 | 1.077 |
| R  | 0.102 | 0.268 | 0.178 |

According to the range R shown in table 3.3, for this experimental model, the influence of tenon slope on the load transfer efficiency of tenon and groove joint is higher than that of tenon length and tenon thickness.

According to the range R shown in table 3.4, for this experimental model, the influence of tenon thickness on the maximum stress of convex slab is higher than that of tenon length and tenon thickness.

3.4. Analysis and optimization of the influence trend of various factor

For the design of prefabricated slab, we should not only consider the load transfer efficiency of the prefabricated slab under the action of vehicle load, but also consider the stress of the prefabricated slab itself. Therefore, the influence trend diagrams of the length of the tenon, the thickness of the tenon and the slope of the tenon on the load transfer coefficient and the maximum stress of the slab are drawn. As shown in figure 3.2, figure 3.3, and figure 3.4:

Trend diagram of the influence of various factors on the load transfer coefficient and maximum stress of the convex slab.

It is shown in figure 3.2 that with the increase of tenon length, the load transfer coefficient of tongue and groove joint also increases, and the increase amplitude slows down with the increase of tenon length. With the increase of tenon length, the maximum stress value of convex slab decreases, and the maximum stress value increases when the tenon length is larger than 3 cm. Due to the limitation of parameter range, the optimal tenon length can not be obtained, so the parameter range should be extended in this paper. Single factor influence trend diagram of tenon length on load transfer coefficient and maximum stress of convex slab is obtained, as shown in figure 3.5. It is shown in figure 3.5 that, with the increase of the length of tenon, the load transfer coefficient of tongue and
groove joint also increases. With the increase of tenon length, the maximum stress of convex slab decreases first and then increases, and there is a minimum value at the place where the tenon length is 4 cm. Therefore, the optimal value of the length of tenon should be taken as 4 cm.

![Figure 3.2](image.png)  
**Figure 3.2.** Trend diagram of the influence of tenon length on load transfer coefficient and maximum stress of convex plate.

![Figure 3.3](image.png)  
**Figure 3.3.** Trend diagram of the influence of tenon thickness on load transfer coefficient and maximum stress of convex plate.

![Figure 3.4](image.png)  
**Figure 3.4.** Trend diagram of the influence of tenon slope on load transfer coefficient and maximum stress of convex plate.

![Figure 3.5](image.png)  
**Figure 3.5.** Trend diagram of the effect of tenon length on load transfer coefficient and maximum stress of convex plate.

It is shown in figure 3.3 that with the increase of the thickness of the tenon, the maximum stress value of the convex slab is steadily decreasing; with the increase of the thickness of the tenon, the load transfer coefficient of the tongue and groove joint is reduced. When the thickness of tenon is more than 6 cm, the load transfer coefficient of tongue and groove decreases significantly. Therefore, the optimal value of the thickness of the tenon should be taken as 6 cm.

It is shown in figure 3.4 that with the slowdown of tenon slope, the load transfer coefficient of the tongue and groove joint increases, When the tenon slope is less than 1:3, the load transfer coefficient increases slowly; as the tenon slope slows down, the maximum stress value of the convex slab increases. When the tenon slope is less than 1:3, the maximum stress of convex slab increases slowly. Therefore, considering the actual construction technology, the optimal value of the slope of the tenon should be taken as 1:4.

The final combination of parameters should be selected as follows: tenon length 4 cm, tenon thickness 6 cm, tenon slope 1:4. The load transfer coefficient of the parameter combination is verified by finite element software. Under the combination of parameters, the load transfer coefficient of the model is shown as 99.14%, and the maximum stress of the convex slab is shown as 1.11 MPa.

4. Conclusion

In this paper, the numerical simulation analysis of the new precast concrete pavement slab with additional buckle structure is carried out, and the following conclusions are drawn:
• With the increase of the length of the tenon, the load transfer coefficient of tongue and groove joint also increases. With the increase of tenon length, the maximum stress value of convex slab decreases first and then increases, and there is a minimum value at the place where the tenon length is 4cm.

• With the increase of the thickness of the tenon, the load transfer coefficient of tongue and groove joint will gradually decrease; with the increase of the thickness of the tenon, the maximum stress value of the convex slab is steadily decreasing.

• With the slowdown of slope of the tenon, the load transfer coefficient of the tongue and groove joint increases,and the increase will gradually slow down; with the slowdown of tenon slope, the maximum stress value of convex slab will gradually increase, and the increase will gradually slow down.

• Within the experimental parameter, the optimal parameter scheme of assembled cement concrete pavement snap-on slab is verified as :the length of the tenon is 4cm, the thickness of the tenon is 6cm, and the slope of the tenon is 1:4.

Acknowledgement
This project is supported by National Natural Science Foundation of China (Project No.51178167) and Wuhan Urban Construction Committee project for science and technology (No.201805).

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