Parameters sensitivity analysis of prefabricated prestressed concrete pavement slab

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Abstract. The prefabricated prestressed concrete pavement with assembly construction and prestressing technology has the advantages of rapid construction and reliable quality. In this paper, a three-dimensional finite element model of the pavement structure was established by numerical simulation method. The parameters including the slab dimension, the thickness of the slab, the prestress value and position of the prestress tendon were sensitively analyzed. The results showed that the slab dimension has a critical value of 1m×1m. While the slab is larger than the critical value, the stress of the slab is almost unchanged. The thickness of the slab also has a critical value of 0.12m. When the slab is less than the critical value, the forced mode of the slab will be changed. With the increase of prestress, the stress concentration at the end of the slab will occur, but the maximum stress did not exceed the strength of the material. It is suggested that the prestress value should be 4-5MPa. The lower the position of the prestress tendon in the slab is, the more obvious the anti-arch effect is, and it is safe to set the prestress tendon in the middle of the slab.

1. Introduction

A cement concrete slab is a common form of pavement[1]. However, in some harsh environments, some regions lack the necessary building materials. At the same time, the climate often changes and it often rains. These unfavorable factors have limited the use of cast-in-place concrete for paving pavement. In addition, the concrete material has a compressive strength much greater than its tensile strength. The prestressing technology can improve the tensile strength of concrete[2]. The prefabricated prestressed concrete slab was produced in the factory and it was shipped to the site for construction. So, the environmental factors and the local conditions cannot limit the construction of prefabricated prestressed concrete slab. Prestressing technology may improve the tensile strength of the concrete slab and it can effectively improve the service life of the concrete pavement slab[3-6]. Therefore, it is of great practical significance to research the prefabricated prestressed concrete slab for new pavement structure.

In this paper, the finite element method was used to analyze the sensitivity of different parameters of prefabricated prestressed concrete slab. The main parameters included the slab dimension, the slab thickness, prestress magnitude and prestressing tendon position. Through the numerical simulation
analysis, the variation rules of different parameters were obtained, which provided the theoretical
guidance to determine the reasonable parameters for slab fabrication.

2. Mechanical model

2.1. Foundation model
A three-dimensional finite element model was established according to the actual pavement structure. The actual prefabricated pavement structure consisted of a surface layer, a grout layer (leveling layer), a base layer and a soil base layer. The grout layer (leveling layer) was located between the surface layer and the base layer[7-8]. The grout layer not only can effectively bond the surface layer and the base layer, but also can adjust the elevation of the surface layer to ensure the level of the pavement surface. In this modeling, the thickness of the grout layer was ignored, and it was characterized by the coefficient of friction between the surface layer and the base layer. In order to reflect the characteristics of the semi-infinite foundation, according to the convergence of numerical simulation and the related references, the dimensions of the base layer and the soil base layer of the pavement structure were determined as: length × width × thickness = 20m × 20m × 10.3m, where the thickness of the base layer was 0.3m and the thickness of soil base layer was 10m. The dimension of the single slab was 5m × 2.5m × 0.12m, and the joint width between the slabs was assumed to be 10 mm. The mechanical model of the pavement structure which consisted of 9 pavement slabs was shown in Fig.1 to simulate a multiple slabs system. The longitudinal prestressing tendons and the transverse structural reinforcing bars were arranged in the pavement slabs, and the prestressing tendons were 1×7 strands of steel strands with the diameter of 15.2 mm. Because the concrete slab thickness was thin, the cross-section moment of inertia of the slab was small. Therefore, the prestressing tendons were placed in the middle of the slab from preventing its eccentricity which may cause the buckling and instability of the slab. The prestressing tendons were arranged at a spacing of 500 mm, and the transverse structural reinforcing bars made of HRB400 with a diameter of 8 mm were arranged a spacing of 250 mm. A schematic diagram of the reinforcement of the concrete pavement slab was shown in Fig.2.

![Fig.1 Schematic of pavement structure](image1)

![Fig.2 Schematic of pavement slab](image2)
2.2. Wheel load
A wheel load was taken as a calculated load. The wheel printing area was converted into a uniform rectangular wheel load by the formula (1).

\[
\begin{align*}
L &= 1.205 \times A^{0.5} \\
B &= 0.83 \times A^{0.5}
\end{align*}
\]

(1)

Where \( A \) was the ground contact area of a tire; \( L \) was the wheel printing length of the equivalent rectangular uniform wheel load; and \( B \) was the wheel width.

2.3. Prestressed load
In addition to applying a wheel load on the slab, it was necessary to consider the application of longitudinal prestress in the slab. The prestress was applied by the falling temperature method, and the stress calculation formulas of the falling temperature method was as follows:

\[
\sigma_c = \Delta T E \alpha
\]

(2)

Where \( \sigma_c \) was the tensile control stress from the prestressing tendon; \( \Delta T \) was the required temperature; \( E \) was the elastic modulus of the prestressing tendon; \( \alpha \) was the linear expansion coefficient of the prestressing tendon. After determining the tensile control stress of the prestressing tendon, the calculation formula of the slab prestress \( \sigma_y \) can be derived. The slab prestress \( \sigma_y \) was average stress obtained by pulling all the prestressing tendons in the slab. The forced diagram of the prestressed pavement slab was shown in Fig.3.

![Fig.3 Schematic of prestressed pavement slab](image)

The prestressing tendons were arranged in the middle of the pavement slab. Assuming that there were \( n \) prestressing tendons in the slab, the force \( F_i \) from each prestressing tendon can be obtained by multiplying the tensile control stress \( \sigma_{ci} \) by the nominal cross-sectional area \( A_{pi} \) of the prestressing tendon, as shown in equation (3).

\[
F_i = \sigma_{ci} A_{pi}
\]

(3)

The force \( F_j \) from each prestressing tendon constituted a plane force system. When the force \( F_j \) was simplified toward the mass center of the cross section, because the number and the distance from the mass center of the prestressing tendons were the same, the simplified result was the resultant force \( \sum F_j \) without the bending moment of the cross section. According to the force balance condition, the formula for calculating the average prestress of the cross section can be obtained as follows:

\[
\sigma_y = \frac{\sum_{i=1}^{n} F_i}{wh} = \frac{\sum_{i=1}^{n} \sigma_{ci} A_{pi}}{wh}
\]

(4)

In general, the stress \( \sigma_{ci} \) and the nominal cross-sectional area \( A_{pi} \) of each prestressing tendon were the same, the equation (4) can be further simplified as:
\[
\sigma_y = \frac{n \sigma_c A_p}{w h}
\]

Where \( n \) was the number of prestressing tendon in each slab; \( \sigma_c \) was the tensile control stress; \( A_p \) was the nominal cross-sectional area of the prestressing tendon; \( w \) was the width of the slab; \( h \) was the thickness of the slab.

3. Finite element modeling
There were three key techniques for building a finite element model of a pavement slab. The first was how to apply the prestress. The Link8 element was used to simulate the prestressing tendon, and the prestress was applied by the falling temperature method. The second was how to simulate the contact behavior between the slab and the base layer. In the actual pavement structure, there was a grouting layer. The contact relationship between the pavement slab and the base layer was established by the contact element Conta173 and the target element Targe170. The third was how to simulate the joint between the slabs[9-10]. The actual pavement slabs were connected by aggregate interlocking or force-transmitting rods. The spring element Combin14 was used to simulate the joint, and the stiffness of the spring (joint stiffness) was used to indicate the bearing capacity of the joint. According to the above, the finite element model was building from the bottom to the top of the pavement structure. The wheel load was applied at the most unfavorable position of the single pavement slab (the position in the longitudinal joint edge). The base layer and the soil layer were connected by a common node, and the perimeter and bottom of the soil layer were restrained. The three-dimensional finite element model of the pavement structure was shown in Fig.4. Fig.4a) was the geometric model; Fig.4b) was the whole finite element model; Fig.4c) was the 9 pavement slab of the finite element model; Fig.4d) was the joint which was simulated by the spring element Combin14 to connect the concrete element Solid65.
4. Analysis of results

4.1. Influence of slab dimension

The dimension of the slab was the primary parameter for the design of the pavement structure. Referring to the relevant literature, the slab dimension was initially determined to be 5m×2.5m×0.12m. Taking the slab dimension as a parameter, the influence of slab dimension was further researched by numerical simulation, and the rationality of the preliminary determined slab dimension was verified. The simulation results were listed in Tab.1. The curves of the tensile stress of the slab with the different width were shown in the Fig.5.

| No. | B×L×H /m³ | L/B | δ /mm | σ_L /MPa |
|-----|------------|-----|-------|----------|
| 1   | 1×1×0.12   | 1   | 1.91  | 4.817    |
| 2   | 1×2×0.12   | 2   | 1.832 | 5.571    |
| 3   | 1×3×0.12   | 3   | 1.831 | 5.563    |
| 4   | 1×4×0.12   | 4   | 1.834 | 5.555    |
| 5   | 1×5×0.12   | 5   | 1.836 | 5.552    |
| 6   | 1×6×0.12   | 6   | 1.836 | 5.551    |
| ... | ...        | ... | ...   | ...      |
| 36  | 5×8×0.12   | 1.6 | 1.789 | 5.428    |
| 37  | 5×10×0.12  | 2   | 1.788 | 5.428    |

Note: B-slab width; L-slab length; H-slab thickness; δ-deflection; σ_L-tensile stress.

The following conclusions can be seen from Tab.1 and Fig.5.

1) When the slab width was constant, the tensile stress decreased with the increase of the slab length, except for the 1m×1m slab. But the magnitude of the decreasing was very small.

2) The slab tensile stress of the dimension of 1m×1m was 4.817MPa, which was the minimum tensile stress in all the slab. Its deflection was 1.91mm, which was the maximum in all the slab. The reason was because the smaller the slab area was, the stronger the integer effect of the slab was. The forced performance of the smaller area slab was like a precast concrete block. Therefore, the stress became the smaller and the deflection became the larger. On the contrary, the larger slab area was, the more the local effect was obvious. Therefore, the stress became the larger and the deflection became the smaller. It can be clearly seen from the comparison of the deformation and the tensile stress contour between the minimum area slab 1 m× 1 m and the maximum area slab 5 m× 10 m, as shown in Fig. 6.

3) When the slab length was constant, the tensile stress decreased with the increase of the slab width. When the slab width was 1m-2m, the variation amplitude of the tensile stress was relatively large. Exceeding the slab width of 2m, the stress was almost unchanged.
4) When the load was constant, the slab dimension had a critical value. When the slab dimension was smaller than the critical value, the slab was forced with the integer effect, which was similar to the precast concrete block. After the comprehensive consideration of forced analysis and convenient construction, the reasonable dimension of the slab was finally determined to be 5m×2.5m.

![Deformation of slab 1m×1m](image1)

![Deformation of slab 5m×10m](image2)

![Tensile stress of slab 1m×1m](image3)

![Tensile stress of slab 5m×10m](image4)

**c) Tensile stress of slab 1m×1m**

**d) Tensile stress of slab 5m×10m**

**Fig.6 Comparison of deformation and stress between the smallest and the largest dimension slab**

### 4.2. Influence of slab thickness

The slab thickness has an important influence on the mechanical performance of the precast prestressed concrete pavement structure. A reasonable slab thickness can not only help the pavement structure to improve the bearing capacity and durability, but save the project money. Referring to the relevant literature, the slab thickness was assumed to be 0.12m. In the numerical simulation, the slab thickness was varied from 0.04m to 0.30m to further study the influence of different thicknesses on the mechanical properties of slab. The finite element calculation results were listed in Tab.2. Fig.7 was the deflection curve of the different thicknesses of the slab, and Fig.8 was the tensile stress curve of the different thicknesses of the slab.

| No. | B×L /m² | H /m | δ /mm | σL /MPa |
|-----|---------|------|-------|---------|
| 1   | 2.5×5   | 0.04 | 2.081 | 2.801   |
| 2   | 2.5×5   | 0.08 | 1.943 | 4.793   |
The following conclusions can be obtained from Tab.2 and Fig.7 and Fig.8.

1) When the other parameters of the slab were unchanged, the slab bottom deflection decreased linearly with the thickness of the slab. Unlike the deflection of the slab, the tensile stress of the slab bottom increased first and then decreased linearly. The tensile stress curve of the slab bottom was parabolic shape.

2) The research results indicated that it was not good for the thinner thickness slab. The 0.12 m was a critical thickness of slab. When the slab thickness was less than this critical value, a three-dimensional forced effect of the slab will occur. The forced mode of the slab became a film stress, which may cause the local damage of the slab. When the thickness of slab was larger than the critical value, the forced mode of the slab was a unidirectional bending. It was a kind of whole bending forced mode for the slab. This can be seen from the tensile stress contours of several different thickness slab, as shown in Fig. 9. Local failure was a brittle failure, and the bending failure was a kind of ductile failure. Therefore, the thickness of the slab was not less than 0.12 m from the perspective of forced mode.
In addition, other factors needed to be considered for determining the slab thickness, such as assembly, transportation, self-weight and prestress. When the slab was too thick, the single slab self-weight was large, resulting in some other problems such as transportation and hoisting. When the slab was too thin, it was not convenient for the applying prestress. Therefore, it was reasonable to propose that the slab thickness is 0.12 m.

### 4.3. Influence of slab prestress

#### 4.3.1. Prestress magnitude

The prestressing tendon can improve the tensile capacity and the integral stiffness of slab, thus enhancing the bearing capacity and durability of the slab. In order to study the mechanical property of slab with different prestress, the prestress was taken as a parameter and the range of prestress was 0-5 MPa. The falling temperature method was used to simulate the prestress in the slab. The calculation results were listed in Tab.3. Fig.10 were stress contours of slab under different prestress, and Fig.11 was a stress comparison. Because of the prestress, the stress concentration may occur at the end of the pavement slab, and the maximum value may be located at the end of the pavement slab no mid-span of slab.

**Fig.9 Main tensile stress contours of slab with different thickness**

| Tab.3 Calculation results for different prestress slab |
|---|---|---|---|---|---|---|---|
| No. | \(\sigma_y/\text{MPa}\) | \(q/\text{MPa}\) | \(\delta/\text{mm}\) | \(\sigma_{y1}/\text{MPa}\) | \(\sigma_{L1}/\text{MPa}\) | \(\sigma_{y2}/\text{MPa}\) | \(\sigma_{L2}/\text{MPa}\) | \(\sigma_c/\text{MPa}\) |
| 1 | 0 | 1.58 | -1.798 | -6.044 | 5.416 | -6.044 | 5.416 | 0 |
Note: $\sigma_y$-slab prestress; $q$-slab load; $\sigma_{y1}$-midspan compressive stress; $\sigma_{L1}$-midspan tensile stress; $\sigma_{y2}$-whole compressive stress; $\sigma_{L2}$-whole tensile stress; $\sigma_c$-tensile control stress.

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 2 | 1 | 1.58 | -1.801 | -7.011 | 4.471 |
| 3 | 2 | 1.58 | -1.804 | -7.977 | 3.528 |
| 4 | 3 | 1.58 | -1.807 | -8.943 | 2.586 |
| 5 | 4 | 1.58 | -1.810 | -9.910 | 1.643 |
| 6 | 5 | 1.58 | -1.814 | -10.878 | 0.701 |

a) Tensile stress at prestress of 0 MPa
b) Tensile stress at prestress of 1 MPa
c) Tensile stress at prestress of 2 MPa
d) Tensile stress at prestress of 3 MPa
e) Tensile stress at prestress of 4 MPa
f) Tensile stress at prestress of 5 MPa

Fig.10 Tensile stress contours of slab with different prestress
The following conclusions can be obtained from Tab.3 and Fig.10 and Fig.11.

1) The tension stress of mid-span section of slab decreased linearly with the increase of prestress.
2) The stress concentration at the end of the slab occurred with the increase of prestress.
3) The slab was made of reactive powder concrete. Its compressive strength was greater than 100 MPa, and its tensile strength was greater than 12 MPa. When the prestress in the slab changed from 0-5 MPa, the tensile stress in the mid-span of the slab ranged from 0.704 MPa to 5.416 MPa; the tensile stress in the whole slab ranged from 5.416 MPa to 7.04 MPa; the compressive stress in the whole slab ranged from -6.044 MPa to -25.893 MPa. The maximum tensile and compressive stresses did not exceed the strength of RPC100, and the concrete slab did not be destroyed.
4) The prestressing tendon of slab was made of steel stranded wire with diameter of 15.2 mm, and the ultimate strength standard value was 1860 MPa. When the prestress in the slab was 1 MPa, 2 MPa, 3 MPa, 4 MPa and 5 MPa, the tensile stress of the steel stranded wire was 353 MPa, 703 MPa, 1059 MPa, 1412 MPa and 1766 MPa, respectively. Therefore, from the point of view of fully utilizing the steel stranded wire and the safety, it was suggested that the prestress value should be 4-5 MPa.

4.3.2. Location of prestressing tendon
The stress of slab was not only related to the magnitude of prestress, but also to the location of prestressing tendon. The influence of three different location of prestressing tendon on the mechanical properties of pavement slab was investigated. The locations were set in the middle 1/2 of the slab, the lower middle 1/4 of the slab and the slab bottom. The finite element results were listed in Tab.4. The stress contours and deformations of mid-span section were shown in Fig.12.

| No. | σy /MPa | Position | δ /mm | σy1 /MPa | σL1 /MPa |
|-----|--------|---------|-------|----------|----------|
| 1   | 1      | 1/2     | 0.0   | -0.98    | -0.98    |
| 2   | 1      | 1/4     | 0.69  | -0.434   | -1.516   |
| 3   | 1      | Slab bottom | 1.369 | 0.097   | -2.02   |
a) Mid-span section stress of at 1/2 thickness of slab  
b) Deformation of at 1/2 thickness of slab  

c) Mid-span section stress of at 1/4 thickness of slab  
d) Deformation of at 1/4 thickness of slab  

e) Mid-span section stress of at the slab bottom  
f) Deformation of at the slab bottom

Fig. 12 Stress contours and deformations at the different prestressing tendon position

The following conclusions can be obtained from Tab. 4 and Fig. 12.

1) When the prestressing tendons were located at the thickness of 1/2 slab the pavement slab only produced the horizontal deformation, and the stress at the cross-section was -0.97 MPa to -0.99 MPa, which was approximating 1MPa. Stress in numerical calculation was very close to the theoretical value, which verified the correctness of finite element simulation.

2) When the prestressing tendons were set at the thickness of 1/4 slab, the reverse arch appeared obviously. The cross section is not uniformly compressed, but eccentrically compressed. The
compressive stress at the lower side of the slab was -1.516 MPa, and the compressive stress at the upper side of the slab was -0.435 MPa.

3) When the prestressing tendons were set at the bottom of the slab, the reverse arch increased, and the eccentric compression of the mid-span section became more obvious. The compressive stress at the lower side of the slab was -2.02 MPa, and the compressive stress at the upper side of the slab was 0.097 MPa.

4) As the position of the prestressing tendon moved down, the reverse arch increased. The stress of concrete at the middle section changed from the uniform compression to the eccentric compression along with the position of prestressing tendons.

The pavement required a certain smoothness. Therefore, it can be seen that the slab was sensitive to the position of prestressing tendon from the above analysis of numerical simulation results. Considering the convenience of construction and the requirement of pavement smoothness, it was reasonable to install the prestressing tendon in the middle of the slab.

5. Conclusion
In this paper, a three-dimensional finite element model of multi-slab pavement structure was established by finite element method, and the sensitivity of pavement parameters were studied. Through the research, the following conclusions were drawn.

1) The dimension analysis of the slab showed that the dimension of the slab had a critical value at the fixed load. When the area of the slab was smaller than the critical value, the slab mainly worked in the whole effect; when the area of the slab was larger than the critical value, the tension stress at the slab bottom decreased with the increase of the area of the slab, but the amplitude of variation of tension stress was very small.

2) The thickness analysis of the pavement slab showed that the pavement slab had a critical thickness value. When the thickness was less than the critical value, the forced mode of the slab will occur.

3) The prestress analysis of the slab showed that the local stress concentration will occur with the increase of the prestress. The whole stress of slab did not exceed the concrete strength due to RPC concrete material, and the slab did not be destroyed. It was recommended to set about 4-5MPa prestress.

4) The position analysis of the prestressing tendon of the slab indicated that the forced mode of the slab may change from the uniform compression to the eccentric compression as the position of the prestressing tendon moved down. Considering the protective layer of the prestressing tendon and the convenient construction, it was safe to place the prestressing tendon in the middle position of slab.

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