Finite element analysis of rutting on full depth asphalt pavement in port area considering temperature field

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Abstract: To investigate the rutting of the full depth asphalt pavement in the port area, finite element software is used to establish a temperature field model. The vertical deformation of the pavement structure is calculated under five axial load level. Numerical analysis results show that for the proposed pavement structure, vertical deformation is more obvious on the upper layer of the pavement. And it is mainly reflected in the positive deformation of the center of the wheel gap and the negative deformation of the tire centre. In the pavement structure, the middle layer contributes the most to rutting, and the methods for reducing rutting can be explored for this layer of material. The magnitude of the axle load has a great influence on the rut, and the road at the $P_1$ level in the port area is more suitable for full depth asphalt pavement. During the period of 220,000 to 400,000 axle loads, the increase in rut deformation is the largest, and the prevention of rut problems on the road can be carried out at this stage.

1. Introduction
The roads in the port area, as a link connecting various areas of the port, play a very important role in the normal operation of the transportation hub. At present, the main types of pavement used in roads in the port area are cement concrete pavement, interlocking block pavement and asphalt pavement. These three widely used pavement structures have shown some shortcomings and deficiencies in years of use. For example, cement concrete pavements are prone to cracks, poor stability and difficult to repair; Interlocking block pavement has high cost, poor flatness and easy settlement; Traditional asphalt pavement is difficult to effectively solve the common rut problem.

In recent years, a thick layer of asphalt concrete pavement structure built directly on the roadbed has developed rapidly, that is, a full depth asphalt pavement. It is suitable for heavy-duty roads and has a very wide range of applications abroad. Wang Ri-Deng's team studied the applicability of the introduction of full depth asphalt pavement to the roads in the port area, and tried to solve the problem of early damage of asphalt pavement [1]. Xu Gang's team introduced a scientific and instructive design method by studying the full depth asphalt concrete pavement structure in the United States under heavy loads [2]. Therefore, in order to further explore the feasibility of this type of pavement, we will refer to the design concepts related to domestic and foreign full depth asphalt pavements, and learn from the advanced design and construction theory and technology of full depth asphalt pavements in developed countries in Europe and the United States. With reference to Wuhan, the most important inland port city in central China with many ports, and combining with the climatic environment of Wuhan, a full depth asphalt pavement structure suitable for roads in the port area is proposed, and a
A reasonable calculation model is established using finite element software. For the most obvious rutting problem on asphalt pavement, calculation and analysis are carried out in consideration of temperature field. According to the conclusions of the simulation results, the application prospects of this type of paving are evaluated, and some theoretical basis and guidance are provided for the treatment of rut diseases. It is hoped that this research will have a certain effect on improving the design of road structures in the port area, improving the performance of road use in the port area, and reducing the economic losses of road paving in the port area.

2. Model the temperature field
According to related theories, the establishment of asphalt pavement temperature field is mainly controlled by conditions such as solar radiation, air temperature and convective heat exchange, and effective pavement radiation.

2.1. Determining Pavement Structure Parameters
According to "JTS 168-2017 Design Code of Road and Storage yard for Port Area" [3], the selection of road and storage yard pavement structure should comprehensively consider many factors and be determined through technical and economic comparison. The applicable scope of various types of paving structure is also determined. Among them, the load levels suitable for asphalt pavement are mainly \( P_1, P_2, \) and \( P_3 \), and for flexible base layers such as full depth asphalt pavement, the suitable levels are \( P_1 \) and \( P_2 \), as shown in table 1.

| Load level | Load range | Standard single wheel load |
|------------|------------|----------------------------|
|            | Axle load (kN) | Unilateral wheel load (kN) | Wheel load (kN) | Ground pressure (MPa) |
| \( P_1 \)  | \( \leq 150 \) | \( \leq 75 \) | 50 | 0.7 |
| \( P_2 \)  | 150 ~ 300 | 75 ~ 100 | 100 | 1 |

After referring to various types of full depth asphalt pavement structure types [4], a pavement structure solution with the best overall effect was selected, and a two-dimensional plane solid model was built using Abaqus, with a width of 3.75m and a depth of 3m. Along the pavement structure depth directions: 4cm AC-13, 6cm AC-20, 20cm ATB-25, 30cm graded crushed stone, 15cm graded gravel. Then simulate the pavement temperature field under various axle loads in the range of \( P_1 \) and \( P_2 \) load levels.

At the same time, after inquiry, the temperature field analysis thermal characteristic parameters of the pavement structural layer [5] [6] and the representative temperature of 24 hours a day in Wuhan during high temperature can be obtained.

2.2. Analysis of temperature field simulation results
In the simulation process, we defined the course output between the various levels of the pavement structure, so as to obtain the schematic diagram of the change in the internal temperature of the structural layer at each depth of the full depth asphalt pavement in the port area of Wuhan in a day, as shown in figure 1.

From the figure we can see that the temperature change trend of the upper layers of the pavement structure is very similar to the temperature, but there is a certain lag in time. This phenomenon is also more and more obvious along the depth direction of the pavement structure, which indicates that it takes a certain time for the heat to transfer along the depth direction of the pavement structure. In addition, because the asphalt pavement absorbs solar radiation very strongly, it can be clearly seen that the temperature of the pavement structure is much higher than that of the air temperature. The closer the road surface is, the more significant the temperature increase.
3. Simplified model of vehicle load in port area

3.1. Simplified tire load

Because of the road characteristics of the port area: heavy load, large flow, and slow speed, in this case, the shape of the tire contact with the ground is close to a rectangle, and the driving speed can be set to 40km/h.

The simplified model of tire load is shown in figure 2. The radius $\delta$ of the equivalent circle can be determined by the formula $\delta = \sqrt{\frac{4P}{\pi p}}$, the ground contact length $L = \frac{P}{\pi \delta}$.

In order to simulate the pavement situation under the most unfavorable conditions, five groups are selected for simulation in the $P_1$ and $P_2$ load levels, which are:

- **$P_1$ Load level:** ① Axle load 100kN, ground pressure 0.7MPa; ② Axle load 150kN, ground pressure 0.7MPa.
- **$P_2$ Load level:** ③ Axle load 200kN, ground pressure 1.0MPa; ④ Axle load 250kN, ground pressure 1.0MPa; ⑤ Axle load 300kN, ground pressure 1.0MPa.

3.2. Calculation of load action time

Collecting and sorting the traffic volume of the roads in the port area of Wuhan area, we can get the time distribution characteristics of the traffic volume in different periods within 24h.

| Load level | Axle load (kN) | Ground pressure (MPa) | Contact surface calculation load | Cumulative action time (s) |
|------------|----------------|-----------------------|---------------------------------|---------------------------|
| P1         | 100            | 0.7                   | 117371                          | 7545                      |
|            | 150            | 0.7                   | 143678                          | 9236                      |
| P2         | 200            | 1                     | 198412                          | 8929                      |
|            | 250            | 1                     | 221631                          | 9973                      |
|            | 300            | 1                     | 242718                          | 10922                     |

The magnitude of the load acting on the contact surface can be calculated by the formula: $\text{Calculated load} = \frac{P \cdot 10^3}{\delta}$. The cumulative action time after 500,000 axial loads can be
obtained by the formula: 
\[ t = \frac{0.36NP}{nwpBV} \] 
\((N = 500000)\), as shown in table 2.

3.3. Value of material parameters of pavement structure layer
Within a certain temperature change range, the material parameters of the graded crushed stone and gravel of the base layer change little, but the elastic parameters and creep parameters of the surface layer materials such as asphalt mixture have a large change \([7]\). In view of the simulated temperature field, the internal temperature of each layer structure varies between 20°C and 60°C. Therefore, according to many experimental studies of related asphalt mixtures, various parameters of these materials at corresponding temperatures can be obtained.

4. Calculation results and analysis
4.1. Vertical deformation of pavement layers

As can be seen from the figure 3, on the whole, the vertical deformation of each layer of the pavement structure is very different, and the closer to the pavement surface layer, the greater the deformation. Figure 3 (a) and (b) both have obvious positive and negative displacements, that is, uplifts and depressions. But in (c) and (d), the 10cm and 30cm depths are mainly negative displacement. This shows that the rut disease mainly damages the upper layer and the lower layer mainly produces compaction deformation. The asphalt surface layer at the tire load flows to the side due to compression deformation, thereby generating depressions, while the surface layers at the wheel gap and at both sides of the tire are continuously squeezed by the flowing surface material to produce bumps. Especially in the high temperature season, the shear strength of the asphalt mixture is greatly reduced, so rutting problems occur under the cumulative load of the vehicle. Figure 3 also shows that different levels of load have a great effect on vertical deformation. Among the five types of axial loads suitable
for $P_1$ and $P_2$ load levels on asphalt pavement in the port area, as the axial load increases, the tire load time also increases, and the cumulative deformation becomes more and more obvious. As shown in figure 4, the contribution ratio of the pavement structure of each layer to the rut can be calculated.

![Rutting at different depths for each load class](image)

Figure 4. Rutting at different depths for each load class

| Load level | AC-13  | AC-20  | ATB-25 | Graded crushed stone | Graded gravel |
|------------|--------|--------|--------|----------------------|--------------|
| 1          | 23.23% | 59.68% | 16.71% | 0.19%                | 0.21%        |
| 2          | 25.61% | 56.63% | 17.37% | 0.18%                | 0.22%        |
| 3          | 25.02% | 57.53% | 16.97% | 0.21%                | 0.25%        |
| 4          | 25.36% | 56.13% | 18.02% | 0.19%                | 0.26%        |
| 5          | 25.36% | 55.23% | 18.94% | 0.19%                | 0.29%        |

Table 3. Contribution ratio of rut at each load level

Figure 4 shows that the final ruts for the five grades are 1.420 cm, 1.909 cm, 2.288 cm, 2.636 cm and 2.825 cm, respectively. As the load level increases, the ruts produced at all levels also increase steadily. The closer to the road surface, the deeper the ruts and the faster the growth. Table 3 show that AC-20, which contributes the most to rutting, is about 60% in the second layer, followed by AC-13 in the first layer, which has 25%, and ATB-25 in the third layer close to 18%. The bottom two layers of gravel and gravel have little effect on rutting.

4.2. Changes in vertical deformation over time

In the field variable output results, the positive deformation at point E at the center of the wheel gap and the negative deformation at point F at the center of the tire load are the most significant. Output their permanent deformation as a function of the axial load time, and the ruts that vary with the number of axle loads at each load level are calculated, as shown in figure 5 and table 4.
Figure 5. Rutting of each load level as a function of the number of axial loads

Table 4. Cumulative vertical deformation of the surface layer of the road at each load level

| Load level | Total action time(s) | Cumulative vertical deformation(cm) |
|------------|----------------------|-----------------------------------|
| ①          | 7544.99              | 0.548                             |
| ②          | 9235.97              | 0.875                             |
| ③          | 8928.99              | 1.007                             |
| ④          | 9973.01              | 1.259                             |
| ⑤          | 10921.98             | 1.37                              |

According to figure 5. Under the action of 500,000 times of axle load, the rut changes of each load level pavement have certain rules, all of which increase slowly first, start to increase rapidly at a certain loading time, and finally stabilize, and the increase of rut on the upper layer is particularly obvious. Each group of road ruts has a similar slow growth period and fast growth period, and the increase in rut deformation during the period of about 220,000 to 400,000 times is the largest.

5. Conclusion

Due to the peculiar environmental factors and road characteristics of the full depth asphalt pavement in the port area, the rutting problem worth considering. After the above-mentioned simulation analysis, the initial position, size and how to deal with it have been initially understood, and according to specific data, the following conclusions can be drawn:

- The deformation of the pavement structure after repeated loads has obvious rules, and the middle layer is most affected. Vehicle load mainly produces vertical deformation inside the one, two, and three-layer structures within 30cm depth. AC-20 on the second layer of pavement structure contributes most to rutting, reaching almost 60%. In order to reduce the rutting more effectively, an asphalt mixture with higher shear strength at high temperature can be used in this layer, and the thickness of the structural layer can be improved.

- For roads in the port area, the P1 level is more suitable for using full depth asphalt pavement. The ruts under normal use are 1.420cm (P1) and 2.288cm (P2), and the ruts reach 1.909cm (P1) and 2.825cm at the worst (P2). The impact of the load level on the size of the rutting is very significant. In order to ensure the normal use of various functions of the pavement, priority should be given to P1 class roads when designing.

- The simulation results show that the substantial increase in rutting deformation on the road is concentrated during the period of 220,000 to 400,000 axial loads. At each load level, the rutting growth slows down first, then sags slowly, and then there is a rapid growth stage. The larger the load effect, the more obvious this trend becomes. According to this, we can control the use of roads during this period and implement certain maintenance measures in order to effectively prevent rut disease and prolong road life.
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