Structural Analysis of Heavy Haul Road in Mining Area Based on ANSYS

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Abstract: Mining haul roads are subjected to extreme axle loads and frequent traffic, leading to premature deterioration of conventional pavement structures. To enhance load-bearing capacity and service life, this study proposes an innovative composite reinforced concrete pavement system combining C40 reinforced concrete with roller-compacted concrete (RCC). A three-dimensional finite element model incorporating dowel-joint mechanisms was developed using ANSYS software. Numerical simulations were performed under three critical loading conditions — slab corner, longitudinal joint edge, and transverse joint edge — to comparatively analyze deflection patterns and stress distributions between the proposed composite structure and conventional asphalt pavement. Results demonstrate that the reinforced concrete pavement exhibits substantially lower deflection values, confirming superior overall stiffness. The slab corner was identified as the most critical loading position, exhibiting both maximum deflection and peak stress concentrations. Furthermore, dowel bars effectively facilitated load transfer, reducing maximum compressive stress in the loaded slab by up to 26.8% and significantly improving stress distribution homogeneity. These findings validate the structural advantages of the proposed reinforced concrete system for mining heavy-haul applications and provide theoretical support for optimized engineering design.

***Keywords*:** mining road; reinforced concrete pavement; finite element analysis; dowel bar; deflection; stress analysis

1. Introduction

The heavy haul road in the mining area is the key infrastructure in the mining and transportation industry chain of mineral resources. Its service environment has three significant characteristics : large axle load tonnage, frequent load action and poor working conditions. Traditional asphalt pavement is prone to early diseases such as surface cracking, slab bottom void, joint dislocation and structural subsidence under frequent high axle load. Liu Guangming et al. found that the service life of ordinary cement concrete pavement under heavy load conditions in mining area is only 3 to 5 years, which is far lower than the design benchmark of ordinary highway for 10 to 15 years[1].

Early studies by Zollinger and Michael constructed a correlation model between joint load transfer capacity and pavement structure, and verified the key role of dowel bar in reducing joint stress difference[2,3]. Using EverFE software, Zhang Xiaojing found that the maximum principal compressive stress of the panel under 180 kN axle load is 1.65 times that of the standard axle load[4]. Huang et al.established a rolling fatigue load model based on COMSOL, and pointed out that when the load stress level was greater than 0.5, the volume strain increased significantly with the number of fatigue cycles and there was hidden damage[5]. Kim et al.proposed the ARCP structure, which replaces the continuous reinforcement design of CRCP by ‘induced crack + local reinforcement’, reducing the amount of steel by 30% while ensuring that the crack width is controlled within 0.12 mm[6]. Leblouba used polynomial Markov chain and random walk model to point out that the average annual expansion of cracks is 25 mm and the orientation is affected by the coupling of temperature gradient and traffic volume[7]. It is found that the centralized arrangement of dowel bars in the wheel track increases the LTE by an average of 3.015% and can reduce the number of dowel bars[8]. Ma Tao, Zhang Wei and others can make the anti-rutting factor and creep rate ratio of the stress absorbing layer meet the requirements of heavy-duty pavement by adding a certain amount of rubber powder[9,10]. Zhang Xiaocong applied SBS modified stress absorbing layer to reduce the incidence of reflection cracks by 89.2%[11]. Li Jun and Zheng Weiguo put forward that the coefficient of variation of pavement deflection value can be reduced and the service life of pavement can be prolonged by optimizing the reinforcement ratio in CRCP construction of heavy haul road[12,13]. Zhang Li proposed a heavy-duty road design method based on equivalent conversion of axle load, which corrected the influence coefficient of axle load in traditional design and improved the design accuracy[14]. Lin Na pointed out that the composite modification of mineral admixtures (slag, fly ash) and fibers is an important development direction in the future[15].

Based on the structural design of heavy-duty roads in mining areas, this paper intends to use the large-scale general finite element software ANSYS to construct a three-dimensional refined model of reinforced concrete-RCC composite pavement including joint dowel bars. By setting different load conditions, the system compares and analyzes the core performance differences in deflection and stress distribution with ordinary asphalt pavement, and quantitatively evaluates the effectiveness of reinforced concrete pavement and dowel bar structure to improve the overall bearing capacity of pavement and improve the stress concentration phenomenon. The durability design and engineering practice of heavy-duty roads in mining areas provide specific theoretical basis and data support.

2. Road finite element model establishment

In order to accurately simulate the mechanical response of heavy-duty roads in mining areas under extreme loads, based on the design concepts of 'strong base and thick surface' and 'interlayer synergy', this chapter determines the reasonable pavement structure combination and material parameters, and uses the large-scale general finite element software ANSYS to establish a three-dimensional refined numerical model that can reflect the load transfer characteristics of joints. The model comprehensively considers the material nonlinearity, boundary conditions and the most unfavorable position of the load, which lays a solid foundation for subsequent mechanical analysis and performance evaluation.

2.1 Structure and material parameters

This design abandons the structural form of the traditional single concrete slab and adopts a composite double-layer slab system, aiming to give full play to the material characteristics of each structural layer. The upper panel adopts C40 reinforced concrete, which directly bears the impact and wear of the wheel by its excellent tensile and crack resistance. The lower panel adopts RCC (Roller Compacted Concrete), with its high strength and good integrity, as the main bearing and diffusion layer. This 'rigid-rigid' combined structure effectively improves the overall stiffness of the pavement. In order to accurately simulate the mechanical behavior at the joint, a dowel bar member is added to the model. The key mechanical parameters are mainly determined according to the 'Highway Cement Concrete Pavement Design Code' (JTG D40-2011) and related material test research, as shown in Table 1.

Table 1. Pavement structure and material parameters

Material No.	Name of the material	Elastic modulus / MPa	Poisson ratio	Thickness / cm
1	C40 concrete	30e9	0.2	30
2	RCC rolling concrete	20e9	0.2	20
3	20cm water-stable gravel	1.5e9	0.25	20
4	18cm Low dose water stable gravel	1.2e9	0.25	18
5	Stone slag replacement	150e6	0.3	60
6	Dowel bar	200e9	0.3	3.6

2.2 Finite element module method

In order to better simulate the stress and deflection between the load-bearing plate and the non-load-bearing plate, the specification of the pavement slab is 10 m × 9 m. In order to study its load transfer capacity at the joint, four separate concrete slabs are established by ANSYS software. The solid structure adopts SOLID185 element, the dowel bar adopts LINK180 element, and the dowel bar spacing is 250 mm. The concrete slab and the dowel bar are connected by node coupling. The connection between the concrete slab and the roller compacted concrete layer adopts the method of node merging, which is not merged at the joint and not connected between the slabs. Thus, a physical separation is naturally formed in the model to better simulate the slit structure. The overall model is shown in Figure 1.

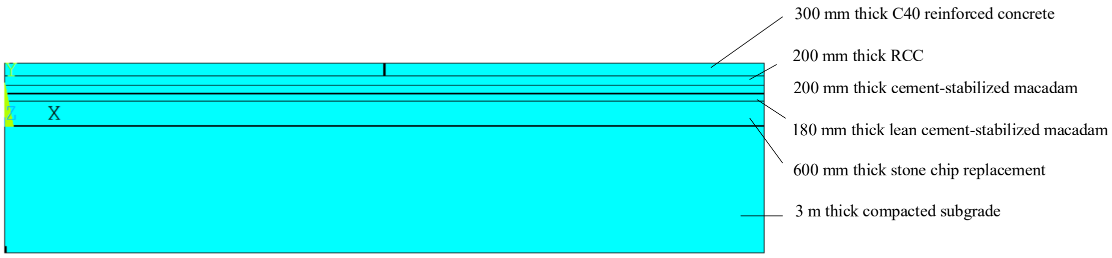
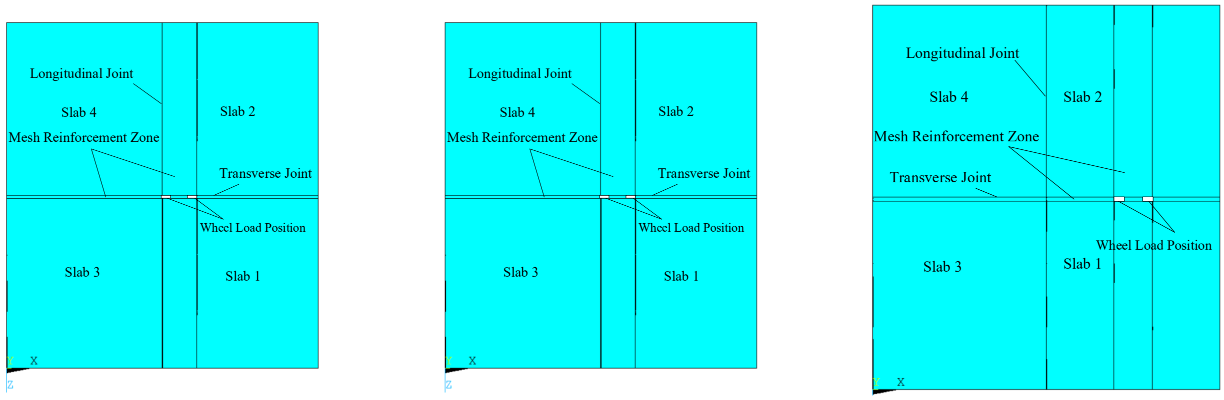


Figure 1. Pavement structure model

2.3 Boundary conditions and load position applied

The model applies three-direction (x, y, z) displacement constraints to limit the overall rigid displacement of the model.

According to the pavement design theory, when the wheel load acts on the plate angle, the plate will produce the maximum deflection and bending moment, which is one of the most unfavorable load positions of the structure. In order to comprehensively evaluate the pavement performance, three typical load conditions were set up in this study : plate corner (wheel pressure acting on the corner area of a single plate), longitudinal joint plate (wheel pressure acting on the middle of the longitudinal joint edge), transverse joint plate (wheel pressure acting on the middle of the transverse joint edge). Referring to the axle load of common transport vehicles in the mining area, the single wheel load applied by the model is 25 kN, and it is directly applied to the corner of the plate or the node at the corresponding position in the plate in the form of uniform pressure (wheel pressure). The specific location of the load is shown in Fig.2. In order to accurately reflect the local response under load, mesh refinement is implemented in all load areas.



(a) The wheel pressure is located at the plate angle.

(b) The wheel pressure is located in the longitudinal joint plate

(c) The wheel pressure is located in the transverse joint plate

Figure 2. The schematic diagram of wheel pressure application position

3. Simulation results and analysis

3.1 Analysis of heavy haul road and ordinary asphalt concrete pavement structure

Deflection value is an important index to measure the deformation degree of pavement under load, which directly reflects the bearing capacity and structural performance of pavement. By comparing the deflection values of the concrete slab and the ordinary pavement structure at different load positions, as shown in Figure 3. It can be seen that in the ordinary asphalt pavement structure, the pavement deflection values under different load application positions are 0.453 mm, 0.451 mm, 0.451 mm, respectively, indicating that the structural response is not sensitive to the load position. This is due to the flexible or semi-rigid structure of the ordinary asphalt pavement structure. Under the load, the stress of this structure spreads downward and around in a wider conical area. The structural layers below the load application point work together to effectively disperse the concentrated load to a wider range of subgrade, resulting in the final deflection magnitude of the direct action area tending to be consistent regardless of whether the load is applied to the plate corner or the plate.

Under the action of load, the deflection value of reinforced concrete pavement is much smaller than that of ordinary pavement structure, which reflects the higher overall stiffness of reinforced concrete pavement in resisting deformation. The deflection values of reinforced concrete pavement under three working conditions of slab corner, longitudinal joint plate and transverse joint plate are 0.167 mm, 0.116 mm and 0.134 mm respectively, which are far lower than the corresponding values of asphalt pavement. Because the reinforced concrete pavement is a rigid pavement, it mainly depends on the stiffness and bending moment of the slab. Due to the lack of sufficient support, there is a significant stress concentration effect in the slab corner area, which is manifested as large deflection. The middle area of the plate is constrained by the surrounding plate body, the stiffness is greater, and the deflection is relatively small. The existence of the dowel bar reduces the deflection value of the pavement to a certain extent. After applying the dowel bar, the deflection values at the corner of the plate and the middle position of the transverse joint plate are reduced by 4.8% and 6% respectively. At the same time, the deflection value of the non-load applied plate is also generally reduced, which indicates that the dowel bar does not completely transfer the deformation to the adjacent plate, but by enhancing the integrity, so that multiple plates participate in the force, thereby reducing the absolute deformation of the whole area and improving the overall stiffness and service performance of the pavement.

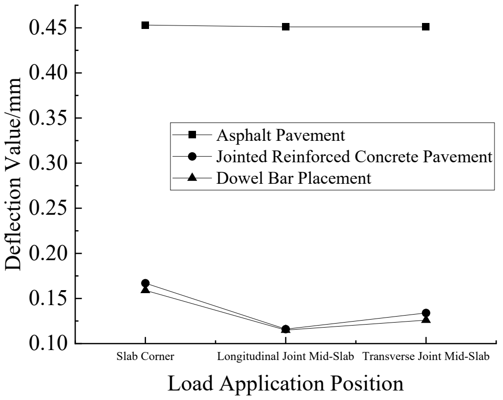
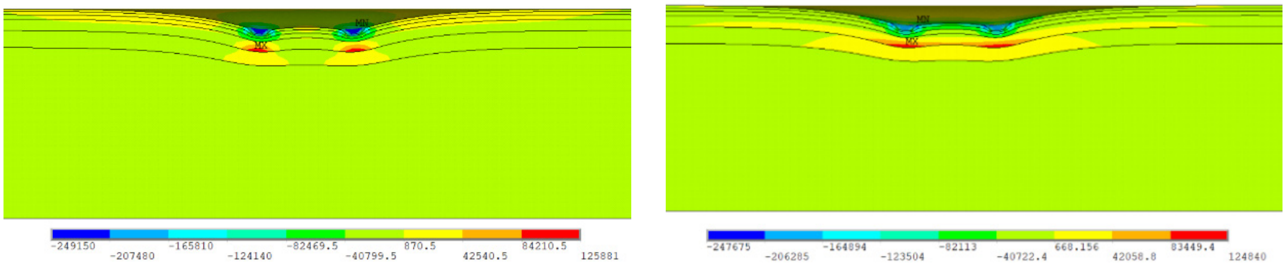


Figure 3. Deflection values of different pavement structures

3.2 Stress analysis of reinforced concrete pavement

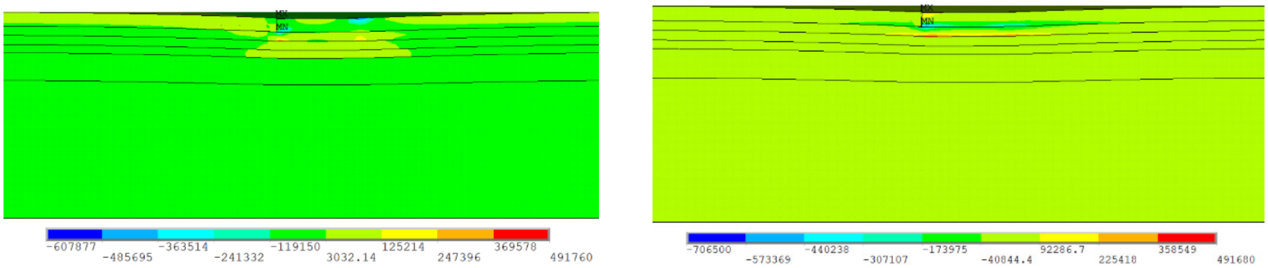
3.2.1 Stress distribution of reinforced concrete pavement and ordinary asphalt pavement

Ordinary asphalt pavement relies on the overall stiffness of each layer structure to diffuse the load stress and disperse it to the soil foundation. The reinforced concrete pavement mainly relies on the stiffness and strength of the concrete slab itself to bear the load, and distributes the load to the larger soil foundation area like a slab. The stress along the transverse seam (x) direction and the longitudinal seam (z) direction is shown in Figure 4. It can be seen from the figure that the stress cloud diagram in the x and z directions of the ordinary pavement has obvious tensile and compressive stress peaks, and the stress concentration area and the influence depth are large. The stress peak of the stress cloud diagram in the x and z directions of the reinforced concrete pavement is significantly reduced, the stress distribution is more uniform, and the influence range is smaller. This shows that the reinforced concrete pavement can more effectively diffuse the load to a larger area of the subgrade through its higher plate stiffness, thus significantly alleviating the stress concentration phenomenon and improving the overall deformation resistance and durability of the structure.



(a) x-direction stress of ordinary pavement

(b) The z-direction stress of ordinary pavement



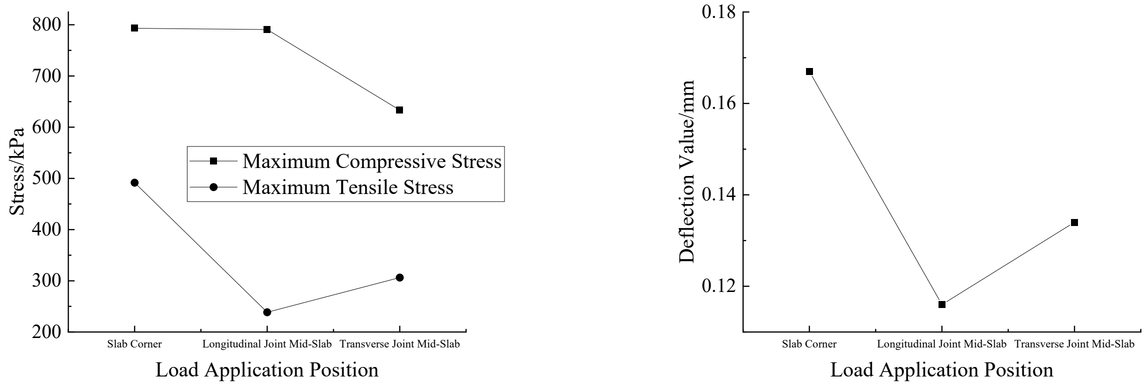
(c) Stress in x direction of reinforced concrete pavement

(d) The z-direction stress of reinforced concrete pavement

Figure 4. The stress distribution of ordinary pavement and reinforced concrete pavement along different directions

3.2.2 The most unfavorable load position of reinforced concrete pavement

Based on the numerical simulation results, the mechanical response of three typical load positions (plate angle, longitudinal joint plate, transverse joint plate) of concrete slab without dowel bar is compared and analyzed. It is confirmed that the plate angle loading is the most unfavorable working condition, and its comprehensive mechanical index is significantly inferior to other positions. As shown in figure 5, when the load is applied to the corner of the plate, the maximum compressive stress, the maximum compressive stress and the deflection value are higher than those at other positions. The maximum deflection under the corner condition is 0.167 mm, which is 30.6% and 24.6% higher than that in the longitudinal joint plate (0.116 mm) and the transverse joint plate (0.134 mm), respectively. The deflection transfer ratio of adjacent plates is as high as 76.6% ~ 83.2%, forming a large-scale collaborative deformation, the structural anti-deformation ability is significantly weakened, and there is a lack of sufficient lateral constraints to limit the rotation and displacement of the plate. As a result, severe stress concentration occurs in the local area around the load point, forming a mechanical imbalance state of ‘single point force-multi-point weakness’. The corner region of the plate is subjected to two-way stress in both the transverse and longitudinal directions at the same time, which is different from the stress mode of one-way stress in the middle position of the plate. The superposition effect of the two-way stress makes the local stress state of the plate corner complex : the compressive stress in the longitudinal direction and the tensile stress in the transverse direction are coupled with each other. On the one hand, the absolute value of the compressive stress is increased, and on the other hand, the tensile stress is more likely to reach the tensile strength limit of the concrete. This two-way stress superposition effect further amplifies the risk of crushing failure and cracking failure of the plate corner.



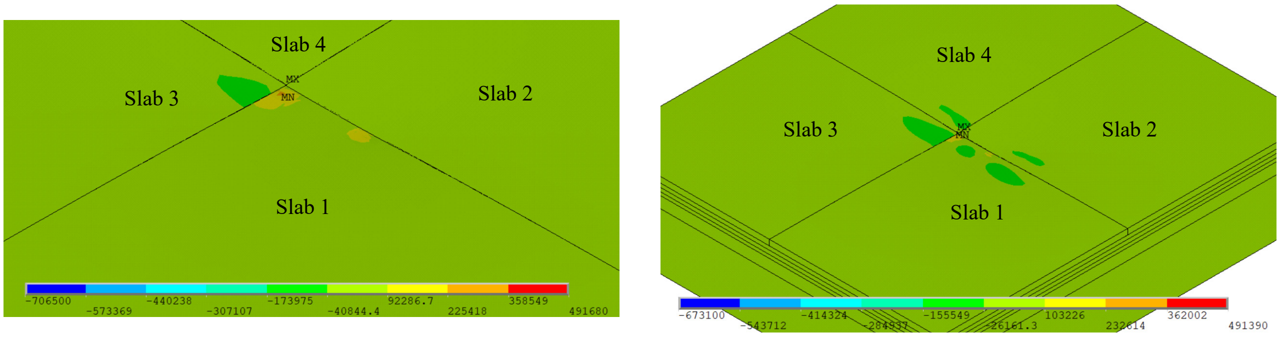
(a) The maximum tensile and compressive stress at different loading positions

(b) Deflection at different loading positions

Figure 5. Comparison of stress and deflection under different load positions

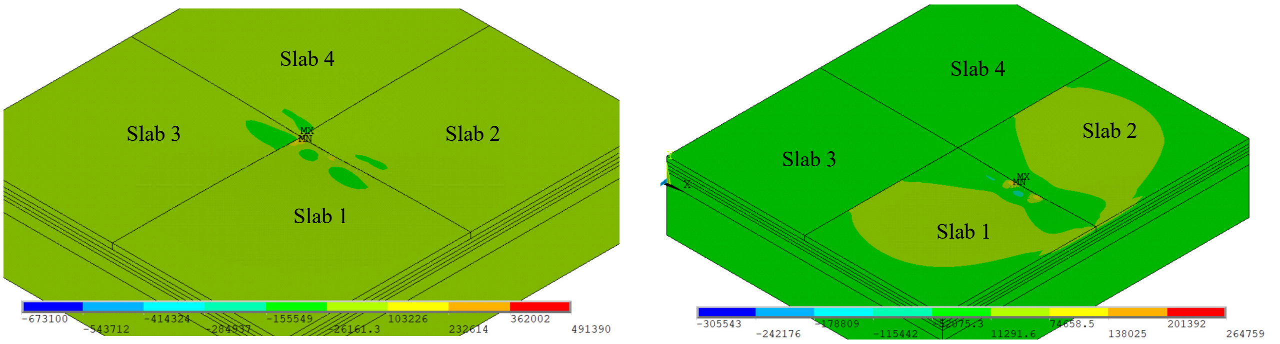
3.2.3 Influence of dowel bar on load distribution

As an important force transmission element at the joint of rigid pavement, the dowel bar is particularly critical to the optimization of load distribution and stress state. As shown in Figure 6 (a) and (b), when the load is applied to the corner of the plate 1, the maximum compressive stress decreases from 706.5 kPa without the dowel bar to 673.1 kPa after the dowel bar is added, a decrease of 4.7%, and the overall force of the pavement slab decreases from 40.8 kPa to 26.3 kPa, a decrease of 35.7%. It can be seen that the dowel bar can transfer part of the pressure of the load-applying plate to the adjacent plate, reduce the stress concentration of the load-applying plate, so the absolute value of the compressive stress is significantly reduced. As shown in Figure 6 (c) and (d), when the load is applied to the middle of the transverse joint of plate 1, the maximum compressive stress decreases from 417.4 kPa without the dowel bar to 305.5 kPa after the dowel bar is added, with a decrease of 26.8%, and the stress level of the adjacent plate increases significantly. The stress cloud diagram shows that the stress concentration area is large when there is no dowel bar, the load is mainly borne by the applied plate alone, and the stress of the adjacent plate is very weak. After setting the dowel bar, the stress distribution is more uniform, the concentrated area is significantly reduced, and the adjacent plates participate in the force and realize the load sharing. This shows that the dowel bar realizes the effective redistribution of the load between the plates by enhancing the cooperative working ability between the plates, thus improving the overall force balance and bearing efficiency of the pavement structure.



(a) The stress in the z direction of the plate 1 angle is applied without the load of the dowel bar.

(b) The stress in the z direction of the plate 1 angle is applied by the load of the dowel bar.



(c) The z-direction stress in the middle of plate 1 is applied by the load without dowel bar.

(d) The stress in the middle z direction of plate 1 is applied by dowel bar load.

Figure 6. Stress distribution of dowel bar under different load positions

4. Conclusion

Compared with ordinary asphalt pavement, the composite rigid pavement structure of ‘C40 reinforced concrete + RCC’ can significantly reduce the deflection. Through its huge overall stiffness, the maximum deflection value under load is reduced by about 60%-70%, which greatly improves the anti-deformation ability of the pavement.

This kind of ‘rigid-rigid’ combination structure not only gives full play to the high strength characteristics of concrete materials, but also effectively spreads the load to a wider range of subgrade through the cooperative work of double-layer plates, thus fundamentally improving the stress state of the structure. It is more suitable for the harsh working conditions of large axle load and strong impact.

The slab corner is the most unfavorable load position of the heavy-duty reinforced concrete pavement in the mining area. Under this working condition, the pavement not only shows the maximum deflection value and the highest stress level, but also forms a complex two-way stress superposition effect because it is in a two-way free state and lacks effective lateral constraints. Therefore, in the design and construction, the slab corner area must be taken as the key control part, and measures such as local reinforcement, optimization of cutting form or enhancement of foundation support should be considered.

The dowel bar can effectively optimize the lateral load transfer, reduce the peak compressive stress of the load applied plate by 4.7% to 26.8%, and make the stress distribution more uniform, realize the multi-plate cooperative force, and significantly reduce the stress concentration.

References

[1] Liu G M. Damage problems and design optimization of cement concrete pavements for heavy-load roads[J]. Transpo World, 2023, (Z1): 161-163.

[2] Zollinger D G, Soares J. Performance of continuously reinforced concrete pavements: volume VII: summary[R]. Virginia: Federal Highway Administration,1999.

[3] Michael J H. Advanced pavement design: finite element modeling for rigid pavement joints, report II: model develop-

ment[R]. Washington DC: Department of Transportation Federal Aviation Administration, 1998.

[4] Zhang X J. Numerical simulation analysis of cement concrete pavement[C]//Proceedings of Academic Papers on Traffic Civil Engineering in China (2006). Institute of Highway Engineering, Southwest Jiaotong University, 2006: 181-184.

[5] Wu H, Yinchuan G, Aiqin S, et al. Numerical simulation of internal stress in pavement concrete under rolling fatigue load[J]. International Journal of Pavement Engineering, 2022,23(4):1306-1315.

[6] Kim S, Cho K Y, Lee H J. Advanced reinforced concrete pavement: Concept and design[J]. Construction and Building Materials,2020,231117130-117130.

[7] Moussa L, Mohamad T, Mostafa Z. Probabilistic analysis and simulation of crack propagation in concrete pavements and surfaces[J]. Scientific Reports,2022,12(1):14157-14157.

[8] Zhang C, Wang X, Cui B X, et al. Simulation analysis of dowel bar arrangement modes in cement concrete pavement[J]. Journal of Chang'an University (Natural Science Edition), 2014, 34(04): 25-30.

[9] Ma T. Application of high-performance stress-absorbing layer in highway engineering[J]. Transpo World, 2024, (17): 27-30.

[10] Zhang W. Application of high-performance stress-absorbing layer in highway engineering[J]. Transpo World, 2025, (14): 100-102.

[11] Zhang X C. Analysis of the comprehensive application technology of high-performance stress-absorbing layer in highway engineering[J]. Transpo World, 2023, (25): 55-57.

[12] Li J, Liu Q, Li Z. Construction technology of continuously reinforced concrete pavement for urban heavy-load roads[J]. Building Technology Development, 2016, 43(01): 118-119.

[13] Zheng W G, Chang B, He Y, et al. Application of continuously reinforced concrete pavement in heavy-load roads in Qingshan area[J]. China Municipal Engineering, 2018, (02): 33-35, 38, 130.

[14] Zhang L. On pavement design methods for heavy-load roads[J]. Heilongjiang Communications Science and Technology, 2023, 46(08): 29-31.

[15] Lin N. Research status of road concrete under heavy-load traffic[J]. Technology Innovation and Application, 2022, 12(30): 126-129.