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Original Paper

Structural Optimization and Mechanical Performance Analysis of Combined Permanent–Temporary Construction Access Roads under Heavy Loads

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Abstract

Construction access roads constructed for highway projects are frequently subjected to traffic loads that exceed those considered in conventional pavement design. To evaluate the applicability of the permanent–temporary integration concept, a highway project in Shaanxi Province was selected as a case study. Three representative pavement structures were established in ABAQUS and analysed under concrete transport vehicle loading conditions. The simulation results indicate that both the stiffness and thickness of the supporting layer have a significant influence on pavement behaviour. An increase in subgrade stiffness reduces slab stress and promotes load diffusion, whereas a thicker supporting layer is more effective in controlling pavement deflection. Compared with the surface layer modulus, changes in subgrade properties produce a more pronounced effect on the overall structural response. Considering mechanical performance together with construction cost, a single-layer pavement consisting of 30 cm C40 concrete was identified as the most suitable alternative for the investigated project. The findings may provide useful references for the design and optimization of construction access roads subjected to heavy traffic loading.

Keywords

permanent and temporary combined construction, construction access road, heavy load traffic, ABAQUS, subgrade modulus

1. Introduction

Construction access roads serve as important auxiliary facilities during highway and municipal engineering projects. Although these roads are generally temporary, they are often exposed to repeated heavy-vehicle loading throughout the construction period. Their service condition directly affects transportation efficiency, construction safety and environmental performance (Ran et al., 2024; Liu, 2021; Zhu et al., 2020). Earlier studies mainly regarded access roads as temporary facilities and focused on functional requirements such as traffic capacity and geometric design (Wu et al., 2025; Tian et al., 2025; Zhang et al., 2021). With increasing attention to construction safety and infrastructure durability, researchers have gradually shifted their focus to issues related to bearing capacity, deformation characteristics and structural stability. Most available studies investigated individual pavement or bridge components under static loading conditions (Yang et al., 2025), whereas recent finite-element analyses have considered the interaction among pavement, subgrade and bridge systems (Sun et al., 2018; Kazaryan et al., 2022).

In current engineering practice, construction access roads are commonly designed using empirical approaches and simplified calculations. While these methods are convenient for routine applications, they may not adequately represent the effects of repeated heavy-vehicle loading (Yang et al., 2024; Jin-ming, 2020). Consequently, premature cracking, excessive deformation and repeated maintenance are frequently observed during project implementation. To improve resource utilization and reduce repeated construction activities, the concept of permanent-temporary integrated construction has been proposed and gradually adopted in large-scale infrastructure projects (Saleh, Fahad, & Khalid, 2022; Nilsson Vestola et al., 2021).

Despite the increasing use of permanent-temporary integrated construction strategies in highway projects, available studies have mainly focused on construction management and functional design. Quantitative evaluations of pavement behaviour under sustained heavy construction traffic remain limited. In particular, the influence of different structural combinations on stress transfer and deformation characteristics has not been systematically investigated. To provide further insight, a highway project in Shaanxi Province was selected as a case study, and several representative structural schemes were assessed through finite-element simulations.

2. Project Overview and Selection of Typical Construction Access Road Structures

2.1 Project Background

The investigated access road belongs to a highway construction project in Shaanxi Province. The overall route length is approximately 4.8 km, including about 3.9 km planned for conversion into a permanent roadway after completion of construction activities. Heavy vehicles operating on the route mainly include steel-component transport vehicles, concrete mixer trucks and dump trucks. Field observations indicated that concrete mixer trucks were encountered most frequently; therefore, an axle load of 150 kN was selected as the representative loading condition. This value is substantially greater than the standard axle load commonly adopted in conventional highway pavement design.

2.2 Selection Principles

Integrated access-road construction generally involves two service stages. During project implementation, the pavement must withstand intensive heavy-vehicle traffic associated with material transportation and construction operations. Following project completion, the roadway is expected to serve as part of the permanent transportation infrastructure after limited rehabilitation. Consequently, structural reliability, future usability and economic efficiency were all considered during the selection of representative pavement structures.

2.3 Selection of Typical Structures

Through literature research and site visits to ongoing and completed highway projects, three common material combinations were identified:

(1) Surface Layer: Cement concrete (grade C20–C30, thickness 15–25 cm);

(2) Subgrade Layer: Cement-soil, natural gravel, or cement-stabilized gravel (thickness 15–50 cm; thickness varies based on material type);

(3) Base Layer (optional): Gravel, cement-soil, or cement-stabilized gravel, thickness ≥ 15 cm.

Considering material availability, project cost, and on-site heavy load traffic requirements, three representative construction access road structures (as shown in Figure 1) were determined for further analysis and structural optimization.

(a) Typical Structure 1 (b) Typical Structure 2 (c) Typical Structure 3

Figure 1. Typical Construction Access Road Structures

3. Numerical Simulation and Parameter Settings

3.1 Finite Element Model Establishment

For numerical evaluation, three representative construction access road structures were modelled in ABAQUS. The pavement system was represented as a multilayer elastic structure, with each layer assumed to be homogeneous and isotropic. Such assumptions are commonly adopted in pavement analyses because vehicle–pavement interaction occurs over a short loading duration and the materials used in temporary access roads mainly exhibit elastic behaviour under service loads.

The pavement slab adopted in the numerical model measured 5 m in the longitudinal direction and 4 m in the transverse direction. Prior to the formal simulations, three mesh schemes with element sizes of 0.005 m, 0.01 m and 0.02 m were evaluated. The calculated stress difference between the two finer meshes remained below 2%, indicating that further mesh refinement produced only limited improvement in accuracy. Therefore, the mesh size of 0.01 m was selected to balance computational efficiency and numerical precision. C3D8R solid elements were used for the pavement slab and supporting layers, while CIN3D8 infinite elements were assigned to the outer subgrade region to represent the semi-infinite boundary condition.

The cement concrete surface layer and subgrade are fully tied (Tie) to reflect construction continuity and the absence of slippage between layers. The model's longitudinal and transverse boundaries are constrained in the corresponding direction of displacement. The material parameters for the three typical construction access road structures are shown in Tables 1-3. The adopted modelling approach assumes linear elastic behaviour for all materials. Although this assumption cannot fully capture the nonlinear deformation characteristics of granular materials under repeated traffic loading, it is suitable for comparative analyses of structural performance. The simplified model also allows the influence of key design parameters to be evaluated efficiently while maintaining reasonable computational cost.

Table 1. Material Parameters for Typical Structure 1

Pavement Structure	Surface Layer (Concrete C30)	Subgrade (Cement-Soil)	Subbase
Thickness (mm)	200	300	-
Elastic Modulus (MPa)	30000	600	110
Poisson's Ratio	0.15	0.30	0.30

Table 2. Material Parameters for Typical Structure 2

Pavement Structure	Surface Layer (Concrete C30)	Subgrade (Cement-Soil)	Subbase
Thickness (mm)	200	500	-
Elastic Modulus (MPa)	30000	250	110
Poisson's Ratio	0.15	0.30	0.30

Table 3. Material Parameters for Typical Structure 3

Pavement Structure	Surface Layer (Concrete C30)	Subgrade (Cement-Soil)	Subbase
Thickness (mm)	200	300	-
Elastic Modulus (MPa)	28000	1300	110
Poisson’s Ratio	0.15	0.25	0.30

3.2 Load and Boundary Conditions

Considering the actual traffic composition of construction access roads, the axle load of concrete transport vehicles (150 kN) was selected as the design load, and the axle load of steel structure transport vehicles (220 kN) was selected as the maximum load. The load is applied in a single-axle dual-wheel form, with a dual-wheel spacing of 0.32m and an axle spacing of 1.8m. The load application point is located at the center of the longitudinal seam edge to reflect the most unfavorable stress condition. To facilitate finite element discretization, the actual elliptical contact area is simplified to an equivalent square. The tire contact pressure is calculated using Ikeda’s empirical formula, and the results are shown in Table 4.

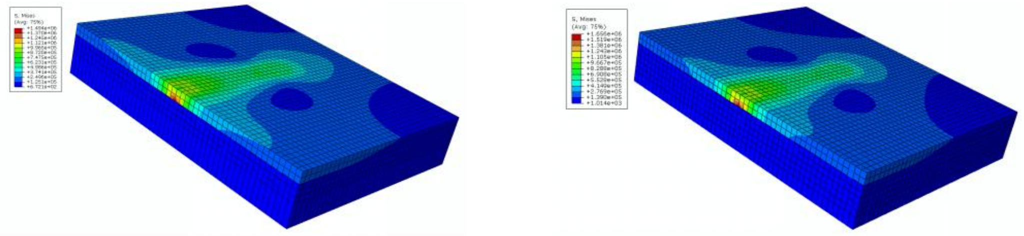
Table 4. Contact Pressure for Two Vehicle Types

Vehicle Type	Axle Load (kN)	Contact Pressure (MPa)	Contact Area (m
Concrete Transport Vehicle	150	0.978	0.038
Steel Structure Transport Vehicle	220	1.272	0.043

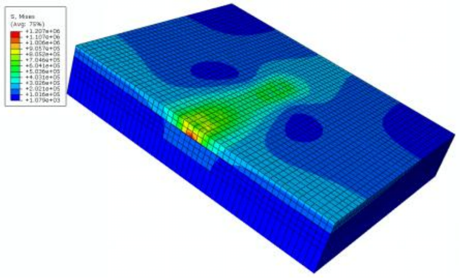
4. Structural Performance Analysis of Construction Access Roads

4.1 Stress State Analysis of Different Construction Access Road Structures

Under the traffic load of concrete transport vehicles, the internal stress distribution of the pavement panels for the three typical construction access road structures is shown in Figure 2. For all three pavement structures, the highest stress developed near the bottom region of the longitudinal joint. The corresponding values were 1.66 MPa, 1.49 MPa and 1.21 MPa for Structures 2, 1 and 3, respectively. The differences indicate that support conditions provided by the underlying layer have a substantial influence on slab stress levels.



(a) Mises Stress Contour for Typical Structure 1 (b) Mises Stress Contour for Typical Structure 2

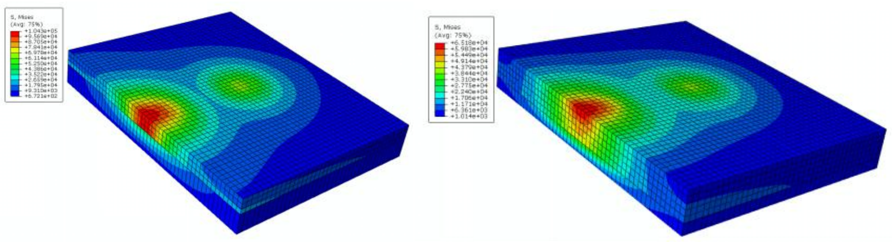


(c) Mises Stress Contour for Typical Structure 3

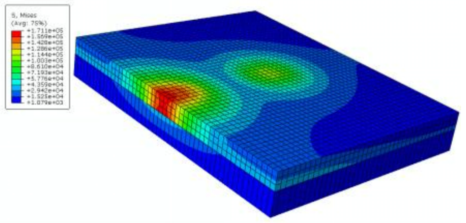
Figure 2. Mises Stress Contour of the Pavement Panels for Typical Construction Access Road Structures

The stress contours in Figure 2 reveal noticeable differences in load-transfer behaviour. For Structure 3, the stress influence area extends over a relatively larger region, indicating that the applied wheel load is distributed more effectively through the pavement system. By contrast, the stress field in Structure 2 remains concentrated around the loading position, reflecting a comparatively weaker stress-dispersion capacity.

Figure 3 presents the stress distribution obtained for the subgrade layer. In all cases, the maximum stress appeared near the bottom of the longitudinal joint. The calculated values were 0.065 MPa, 0.104 MPa and 0.171 MPa for Structures 2, 1 and 3, respectively. These values differ from the stress ranking observed in the pavement slab. The stress field associated with Structure 3 extended over a relatively larger area, whereas a more localized response was observed in Structure 2. Such differences reflect variations in the load-transfer characteristics of the three pavement systems. For Structure 1, the combination of a higher surface-layer modulus and a lower supporting-layer modulus produced an intermediate stress response between the other two structures. A comparison between Structures 1 and 3 indicates that both pavement stiffness and support capacity contribute to the overall structural response. Improvements in the supporting layer can effectively reduce slab stress, whereas a higher surface-layer stiffness may partially compensate for weaker support conditions. These findings highlight the need to coordinate the design of both structural layers.



(a) Subgrade Mises Stress Contour for Typical Structure 1 (b) Subgrade Mises Stress Contour for Typical Structure 2



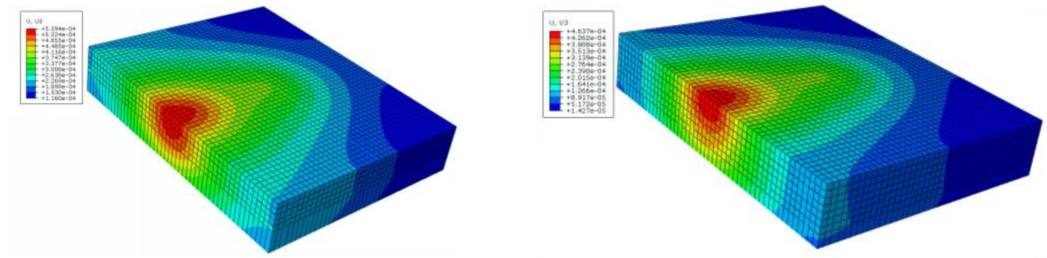
(c) Subgrade Mises Stress Contour for Typical Structure 3

Figure. 3 Mises Stress Contour of the Subgrade for Typical Construction Access Road Structures

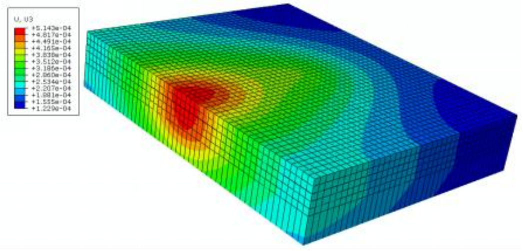
Looking at the range of subgrade stress distribution for the three typical structures, Structure 3 has the widest range, showing the best load stress dispersion; Structure 1 follows with moderate stress distribution and dispersion; Structure 2 has the smallest range and the most concentrated stress. The observed stress-distribution patterns demonstrate that a stiffer supporting layer participates more actively in load carrying, thereby reducing stress concentration within the pavement slab.

4.2 Deflection Analysis of Different Construction Access Road Structures

Under the traffic load of concrete mixer vehicles, the deflection distribution for the three typical construction access road structures is shown in Figure 4. The largest pavement deflection was concentrated near the wheel-loading position along the longitudinal joint, as illustrated in Figure 4.



(a) Deflection Contour for Typical Structure 1 (b) Deflection Contour for Typical Structure 2



(c) Deflection Contour for Typical Structure 3

Figure 4. Deflection Contour of Typical Construction Access Road Structures

The maximum deflection and maximum vertical displacement for the three construction access road structures were calculated, and the results are shown in Table 5. Table 5 indicates that Structure 1 produced the largest deflection, whereas Structure 2 showed the smallest value among the three alternatives.

Table 5. Maximum Deflection and Maximum Vertical Deformation of Typical Structures

Road Structure Type	Maximum Deflection (mm)			Maximum Vertical Deformation (mm)		
	Surface Layer	Subbase	Subgrade	Surface Layer	Subbase	Subgrade
Structure 1	0.559	0.555	0.511	0.004	0.044	0.511
Structure 2	0.464	0.46	0.351	0.004	0.109	0.351

As shown in Table 5, the vertical deformation values of the surface layer were very close for all three pavement structures, indicating that changes in the supporting configuration had limited influence on the slab deformation. Differences became more apparent in the lower layers. The largest deformation was recorded in Structure 2, whereas Structure 3 produced the smallest value. This can be attributed to the relatively low modulus of the gravel layer used in Structure 2, which allowed larger displacement to develop under traffic loading. At the same time, the greater thickness of its supporting layer reduced the stress transmitted to the deeper subgrade. These results indicate that deformation behaviour is governed not only by material stiffness but also by structural thickness, and the interaction between the two factors should be considered in pavement design.

The numerical results show that different structural configurations produce distinct stress-deformation characteristics. Increasing support stiffness contributes to lower pavement stress, whereas increasing support thickness is more effective in limiting structural deformation. Therefore, both factors should be considered simultaneously during structural design.

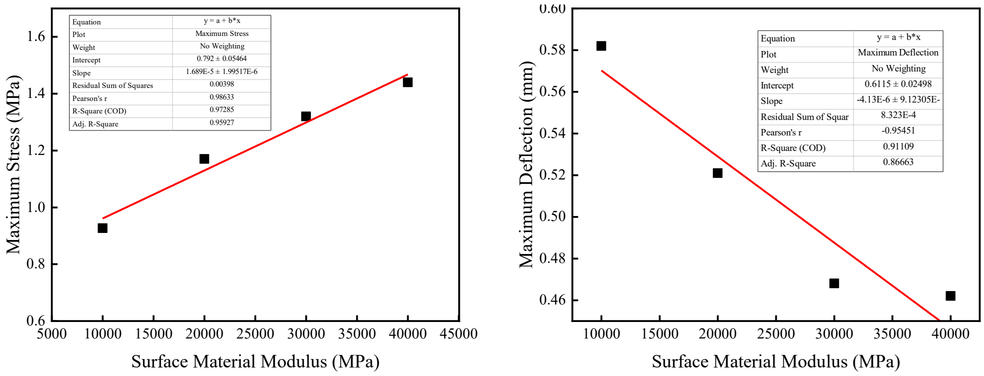
5. Sensitivity Analysis of Material Parameters for Different Structures

A sensitivity analysis was carried out by modifying the elastic modulus values assigned to the surface layer and subgrade. For each parameter combination, the stress distribution and deformation characteristics of the pavement were calculated. The obtained results were then used to compare the influence of different stiffness levels on structural performance.

5.1 Influence of Surface Layer Material Modulus on Construction Access Road Mechanical Performance

In this study, the elastic modulus assigned to the surface layer was varied from 10 GPa to 40 GPa. The selected values were chosen with reference to commonly reported material properties in pavement engineering practice. For each calculation case, the remaining model parameters were kept unchanged so that the influence of surface-layer stiffness could be examined independently. The adopted modulus range covers the typical stiffness levels of asphalt mixtures and cement concrete used in road construction.

The calculated results for the maximum stress and maximum deflection inside the pavement structure under different surface layer moduli are shown in Figure 5. Pavement stress increased progressively as the elastic modulus of the surface layer was raised from 10 GPa to 40 GPa. A stronger growth trend was observed in the higher-modulus range, particularly beyond 30 GPa. In contrast, the calculated deflection values showed only limited variation despite the changes in material stiffness.



(a) Maximum Stress (b) Maximum Deflection

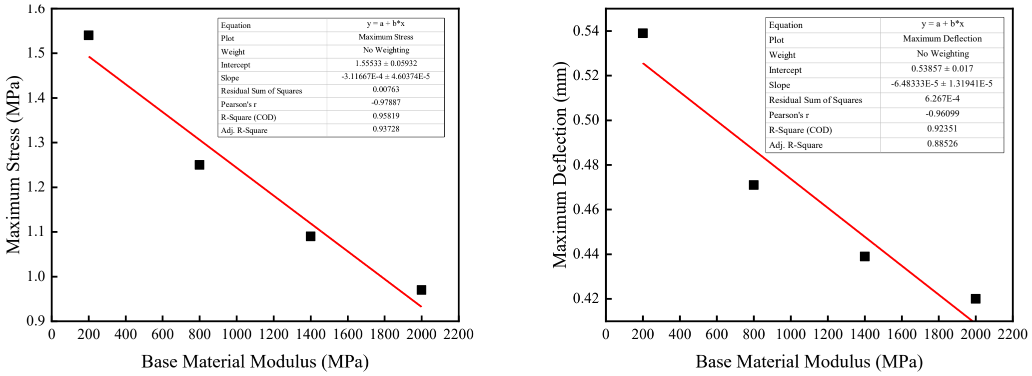
Figure 5. Mechanical Response for Different Surface Layer Materials

When the modulus of the surface layer was increased, a larger proportion of the wheel load was carried by the concrete slab. As a result, the stress transmitted to the lower layers decreased. This load-transfer characteristic improved the overall bearing performance of the pavement structure. For modulus values in the higher range, the variation in structural response became relatively small, suggesting that additional increases in stiffness produced only limited changes in pavement performance.

5.2 Sensitivity of Subgrade Material Modulus

Field investigations and engineering records indicate that granular materials and stabilized materials are the most commonly used options for construction access-road subgrades. Significant differences exist between their mechanical properties. Granular materials generally provide relatively low stiffness, while stabilized materials offer much higher resistance to deformation under traffic loading. The selected modulus ranges (200–2000 MPa) are based on values recommended in JTG D30–2015 for subgrade materials and are consistent with literature dat. Therefore, the subgrade material modulus was varied in four steps: 200 MPa, 800 MPa, 1400 MPa, and 2000 MPa. The analysis focused on the variations in the maximum stress and deflection inside the pavement structure under these different modulus values. In the simulations, only the subgrade modulus was varied, while all other parameters were kept identical to those of Typical Structure 1.

The calculated results for the maximum stress and maximum deflection inside the pavement structure under different subgrade material moduli are shown in Figure 6. Increasing the subgrade modulus from 200 MPa to 2000 MPa reduced the surface-layer stress from 1.54 MPa to 0.97 MPa.



(a) Maximum Stress (b) Maximum Deflection

Figure 6. Mechanical Response for Different Subgrade Materials

Variations in subgrade stiffness produced larger changes in both pavement stress and deflection than variations in surface-layer modulus. The results highlight the dominant role of subgrade support conditions in controlling the mechanical response of construction access roads.

6. Recommended Structures and Validation

6.1 Recommended Construction Access Road Structure for Combined Permanent and Temporary Use

Results obtained from the numerical analyses show that improvements in subgrade stiffness provide greater benefits than increasing the surface-layer modulus. Considering both structural performance and construction cost, two feasible structural alternatives were developed for practical implementation. The structural schemes are shown in Figure 7.

(a) Recommended Structure 1 (b) Recommended Structure 2

Figure 7. Recommended Construction Access Road Structure for Combined Permanent and Temporary Use

During scheme comparison, two pavement configurations were examined. One option employed a 20 cm C20 concrete slab together with a 30 cm cement-stabilized gravel layer. The other adopted a single 30 cm C40 concrete slab. Numerical analysis indicated that the former provided stronger support from the lower layer and achieved a more uniform stress distribution within the pavement system. The latter relied primarily on the concrete slab to resist traffic loading but offered advantages in construction efficiency and material utilization.

The investigated access road was reconstructed from an existing gravel rural road. Years of traffic operation and natural consolidation had improved the density and stability of the original foundation. As a result, the subgrade condition was considered adequate for supporting a single-layer concrete pavement. Under the traffic demand of the project, no obvious structural disadvantage was identified for the C40 concrete scheme. Given its lower construction complexity and better economic performance, this scheme was adopted for the final design.

6.2 Engineering Validation

Based on the project, the construction access road was built using the recommended Scheme (30 cm C40 cement concrete single-layer structure) on the existing gravel pastoral road. Once the main project was completed, the cement concrete construction access road was subjected to heavy traffic from dump trucks, concrete mixer trucks, steel transport vehicles, and other vehicles, resulting in a decline in the pavement's condition. The temporary cement concrete road was then converted into a permanent road, requiring modifications to the temporary road. A survey and evaluation of the damage to the construction access road before the modification were conducted, and the results are shown in Table 6. The survey covered a 500 m long representative section, including 100 concrete slabs. Unevenness was measured using a 3 m straightedge at 10 locations per slab, following the procedure in JTG H20–2019. The Pavement Condition Index (PCI) was evaluated based on visual inspection of distress types (e.g., cracking, spalling) and severity levels, in accordance with the same specification.

From Table 6, the measured unevenness rate was 6.12%, while the PCI value reached 65. Both indicators correspond to a medium condition level according to the maintenance specification. According to the "Highway Cement Concrete Pavement Maintenance Technical Specifications," when the pavement damage condition is medium or above, regular maintenance and local or individual slab repairs can be applied. Therefore, when paving the permanent road, only repairs to the old cement concrete pavement are necessary, without the need for full-section improvement or repairs, saving costs and construction time for the permanent road. This also demonstrates that the construction access road design was reasonable, meeting the traffic volume requirements for construction vehicles while saving on project costs.

Table 6. Survey Results of Construction Access Road Pavement Condition

Survey Item	Survey Result	Rating Level
Unevenness Rate (%)	6.12	Medium
Pavement Condition Index (PCI)	65	Medium

7. Conclusion

Finite-element simulations were performed to evaluate the mechanical behaviour of several representative construction access road structures developed according to the permanent-temporary integration concept. The mechanical behaviour of the investigated pavement structures was evaluated through finite-element simulations under heavy construction traffic loading. Differences in stress transfer, deformation response and material sensitivity were observed among the three structural configurations.

(1) The stress state of the pavement was closely related to the properties of the supporting layer. Structure 3 produced the lowest slab stress and the largest stress-diffusion area, whereas Structure 2 showed a more concentrated stress distribution. The results suggest that a stiffer supporting layer allows a greater portion of the wheel load to be carried by the lower layers of the pavement system.

(2) The three pavement structures exhibited different deformation patterns. The smallest overall deflection was obtained for Structure 2, while Structure 3 achieved better stress reduction within the concrete slab. Variations in both supporting-layer thickness and stiffness affected the deformation response, with layer thickness showing a stronger influence on deflection control.

(3) Increasing the modulus of the surface layer altered both stress and deformation characteristics. Higher stiffness resulted in larger slab stress but reduced pavement deflection. The calculated responses became less sensitive at higher modulus levels, indicating that further increases in stiffness provided progressively smaller benefits.

(4) Compared with changes in surface-layer properties, modifications to the supporting-layer modulus produced larger variations in structural response. Reductions in pavement stress and deformation were more evident as the modulus of the supporting layer increased, confirming its important role in load transfer within the pavement structure.

(5) For the investigated project, the single-layer pavement consisting of 30 cm C40 cement concrete provided a satisfactory balance between structural performance, construction practicality and project cost. Site application showed that the existing foundation conditions were capable of supporting this configuration during the construction period, while only limited rehabilitation work was required before its incorporation into the permanent roadway system.

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