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Study on Deformation Control Effect and Key Influencing Factors of High Modulus Asphalt Concrete in Reconstructed and Expanded Roads

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Abstract: With the continuous growth of highway traffic volume in China, High Modulus Asphalt Concrete (HMAC) has been widely applied in reconstructed and expanded roads due to its excellent mechanical properties and deformation resistance. This study systematically analyzed the influence of HMAC on vehicle passability in reconstructed and expanded roads via Abaqus numerical simulation, focusing on the pavement mechanical response under the working condition of vehicle lane change at the joint position. Additionally, the effects of three key factors—pavement smoothness, wheel pressure, and driving speed—on the vertical displacement response of HMAC pavement layers were systematically investigated. The results show that compared with ordinary asphalt concrete, HMAC pavement layers exhibit smaller vertical displacement and higher smoothness under lane change conditions. Meanwhile, under conditions of low smoothness, high wheel pressure, and high driving speed, HMAC can effectively disperse loads and inhibit deformation accumulation by virtue of its high elastic modulus and low creep characteristics. Particularly at the joints of reconstructed and expanded roads and under complex traffic conditions, HMAC demonstrates excellent deformation control capability, significantly improving vehicle pass ability and riding comfort.

Keywords: High Modulus Asphalt Concrete; Reconstructed and expanded roads; Numerical simulation; Finite element analysis; Pavement response

1. Introduction

In recent years, China has witnessed rapid development in highway transportation infrastructure, and reconstruction and expansion projects have played a crucial role in enhancing road capacity and optimizing traffic network layout. However, differences in material properties and structural discontinuities at the joints between new and old pavements in reconstructed and expanded roads often lead to issues such as pavement deformation and cracking [1-3]. Especially under complex working conditions like lane changes of heavy-duty vehicles, these problems pose challenges to vehicle possibility and driving safety [4]. As a new type of pavement material, High Modulus Asphalt Concrete (HMAC) possesses high elastic modulus, excellent fatigue resistance, and rutting resistance. It can significantly improve the mechanical properties and durability of pavement structures, thus becoming an effective solution to the aforementioned problems [5-7].

Figure 1: Construction Site Diagram of Expressway Reconstruction and Expansion.

Among the indicators for evaluating vehicle passability, pavement smoothness is a key index reflecting the undulation of the pavement surface. Fluctuations in smoothness alter the contact state between wheels and the pavement, thereby affecting load transmission and vertical deformation [8, 9]. However, the deformation response law of HMAC pavement layers under different smoothness levels remains unclear. Wheel pressure varies significantly with vehicle load, and fluctuations in the deformation resistance of HMAC under heavy or overloaded conditions are a key consideration [10, 11]. Changes in driving speed affect the viscoelastic deformation characteristics of HMAC by altering the load action time, yet most existing studies assume a constant driving speed and pay insufficient attention to the dynamic response of HMAC under variable-speed conditions [12-14].

To further explore the application effect of HMAC in reconstructed and expanded roads, this study constructed a three-dimensional finite element model of reconstructed and expanded roads using Abaqus finite element software. The model was used to simulate the pavement mechanical response when vehicles change lanes at joint positions, and to analyze differences in pavement deformation and smoothness between HMAC and ordinary asphalt concrete. Focusing on three key factors—pavement smoothness, wheel pressure, and driving speed—this study reveals the deformation control advantages of HMAC pavement layers under the coupled action of multiple factors, providing theoretical support and a scientific basis for the adaptation to working conditions and structural optimization of HMAC in engineering applications.

2. Model Construction

Based on the actual structural characteristics of reconstructed and expanded roads, a three-dimensional finite element model was established using Abaqus software to simulate the new road, old road, and their joint area. The model includes the old road, new road, and joints, with the pavement structure consisting of an asphalt concrete surface layer, base course, and subgrade. Full constraints were applied to the bottom of the model, and symmetric constraints were applied to the sides to simulate actual boundary conditions (as shown in Figure 2). Gravity was applied as the initial load to the model, and partial pavement structure parameters are listed in Table 1.

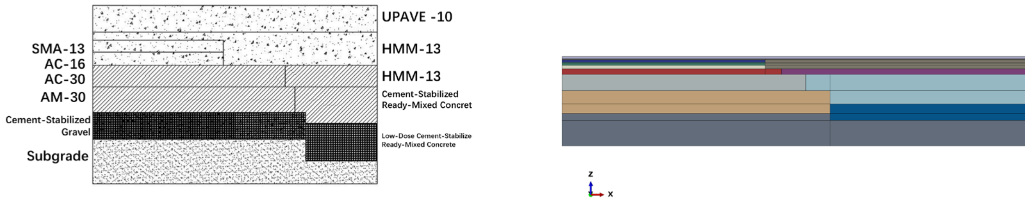


Figure 2: Cross-sectional View and Model of the Expanded Road.

Table 1: Partial Pavement Structure Parameters.

Material Name	Elastic Modulus/ MPa	Poisson ratio
AC-16	1600	0.35
AC-30	1500	0.35
AM-30	1400	0.35
SMA-13	2000	0.25
Cement-stabilized macadam concrete	1800	0.25

According to the standard tire pressure and vehicle load characteristics, the vertical stress of the tire on the ground was set to 1.091 MPa (corresponding to a 20-ton load), and the tire-pavement contact area was simplified to a rectangular contact region. The Abaqus built-in subroutine Vload was used to simulate the moving load of vehicles passing through the joint at a speed of 60 km/h, so as to analyze the pavement response when vehicles change lanes from the old road to the new road.

3. Simulation Analysis

The numerical simulation results of the model (as shown in Fig. 3) indicate that under the action of gravity, the pavement stress distribution of HMAC and ordinary asphalt concrete layers exhibits consistency, with stress mainly concentrated at the interface between new and old pavement materials. This is due to the asynchronous deformation caused by differences in modulus between different materials, leading to local stress concentration, but the overall stress value is relatively low [15].

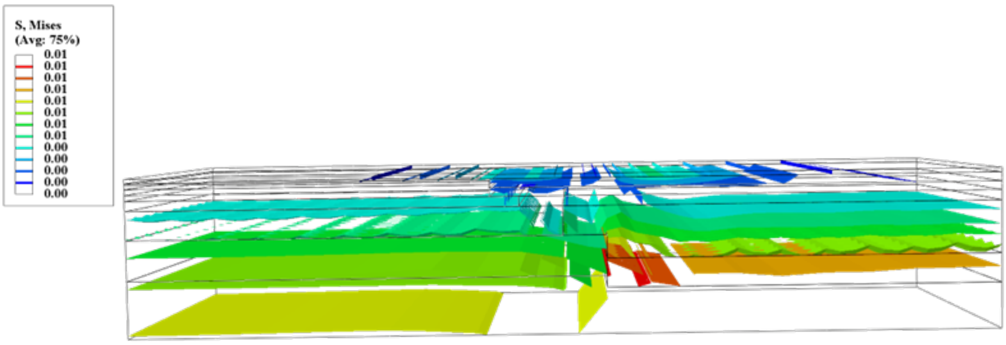
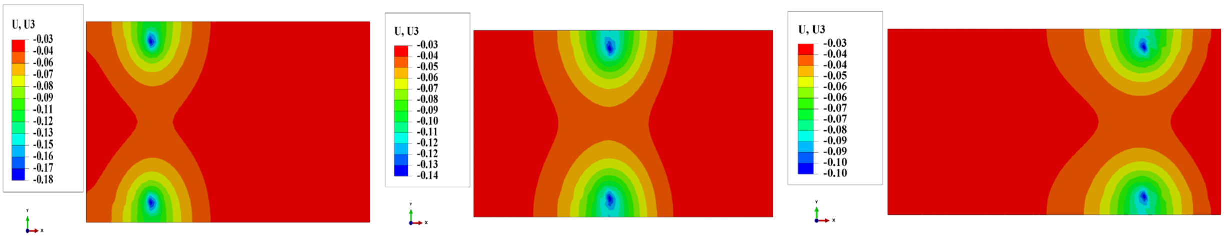


Figure 3: Pavement Stress Distribution Under Gravity Load.

3.1 Influence of Pavement Materials on Pavement Deformation Response

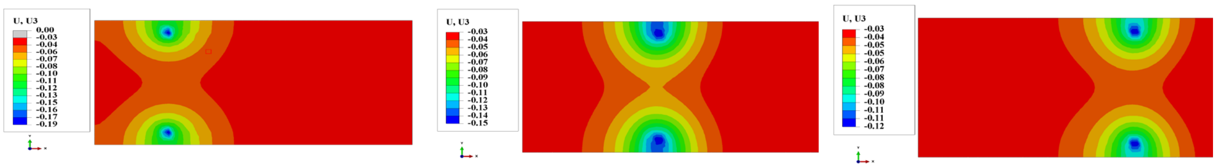
The vertical displacement response of the pavement with HMAC as the surface layer is shown in Figure 4. During the entire process where the vehicle passes from the old road through the road joint to the new road, the maximum vertical displacement of the pavement is 0.18 mm, which occurs when the tire is on the old road section. This is because the subgrade material of the old road has low rigidity, and only a thin layer of HMAC participates in load-bearing, making the pavement prone to deformation under tire load. When the tire travels to the road joint, the vertical displacement distribution of the pavement becomes uniform, and the deformation is significantly reduced. This is attributed to the fact that HMAC participates in pavement load-bearing, further dispersing the applied load to the surrounding area. Meanwhile, the high rigidity of HMAC results in smaller deformation under the same load. In the subsequent incremental steps of the expanded road, the pavement deformation remains stable.



(a) Deformation of the old road section (b) Deformation of the joint section (c) Deformation of the new road section

Figure 4: Vertical displacement distribution of pavement with HMAC surface layer.

The vertical displacement response of the pavement with ordinary asphalt concrete as the surface layer is shown in Figure 5. On the old road section, the vertical displacement of the pavement is larger than that of the HMAC pavement, reaching 21 mm. At the road joint and on the new road section, the vertical deformation of the pavement is smaller compared with that of the HMAC pavement, indicating that the reconstructed and expanded roads with ordinary asphalt concrete as the surface layer have poor load-bearing capacity for vehicles.



(a) Deformation of the old road section (b) Deformation of the joint section (c) Deformation of the new road section

Figure 5: Vertical Displacement Distribution of Pavement with Ordinary Asphalt Concrete Surface Layer.

A line graph of pavement deformation versus displacement distance when the tire passes through different asphalt concrete layers is shown in Fig. 6. It can be observed that when the tire is on the old road section, the curvature of the deformation-displacement curve is basically consistent, with a difference of 1 mm. When the tire is at the joint between the new and old roads, the difference in vertical displacement between the two materials increases to 2 mm. When the tire travels to the new road section, the vertical displacement of the HMAC pavement continues to decrease, while the vertical displacement of the ordinary asphalt concrete pavement first increases and then decreases. This is because ordinary asphalt concrete has low rigidity and undergoes greater deformation under tire pressure after passing through the road joint.

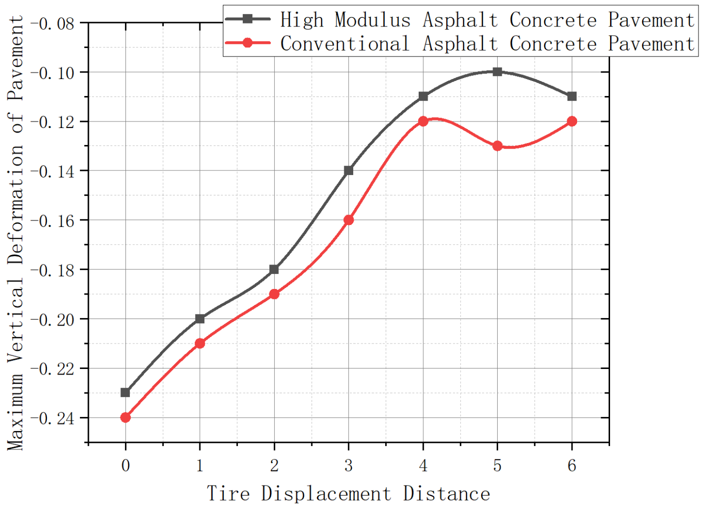


Figure 6: Pavement Deformation Response Under Different Surface Materials.

To further explore the performance advantages of HMAC pavement layers in reconstructed and expanded roads, the scope of simulation analysis was expanded, and the effects of three key factors—initial pavement smoothness, wheel pressure, and driving speed—on the vertical deformation response of the pavement were systematically studied [16, 17].

3.2 Influence of Pavement Smoothness on Pavement Deformation Response

As a core index reflecting the undulation of the pavement surface, pavement smoothness directly affects the contact uniformity between wheels and the pavement, thereby changing the load transmission path and vertical deformation characteristics of the pavement. Based on the original three-dimensional finite element model, this study introduced the International Roughness Index (IRI) to quantify smoothness levels, setting three typical scenarios: Grade A (IRI $\leqslant$ 2.0 m/km), Grade B (2.0 < IRI $\leqslant$ 4.5 m/km), and Grade C (IRI > 4.5 m/km). The vertical deformation response of the HMAC pavement under the vehicle lane change condition (20-ton load, 60 km/h speed) was simulated, and the results are shown in Figure 7.

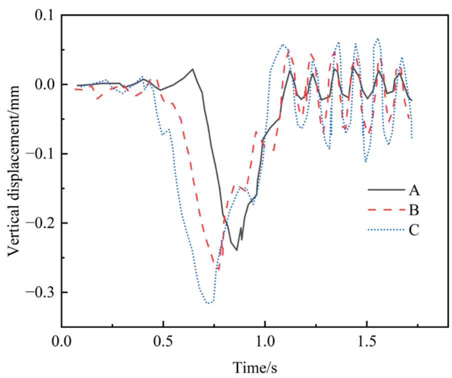


Figure 7: Pavement Deformation Response Under Different Smoothness Levels.

From the perspective of deformation mechanism, undulations on uneven pavements cause dynamic changes in the tire-pavement contact area: under poor smoothness conditions, local convex areas tend to form "point contact," leading to load concentration; while concave areas may cause insufficient local stress diffusion due to increased contact area. For HMAC pavement layers, the high rigidity characteristic derived from their high elastic modulus can effectively inhibit the deformation amplification effect caused by smoothness fluctuations. Under the Grade A smoothness scenario, the vertical deformation of the HMAC pavement is uniformly distributed. During the entire process where the tire travels from the old road through the joint to the new road, the maximum vertical displacement is only 0.24 mm, and the deformation curve is smooth without sudden changes. This is because the smooth surface enables uniform transmission of tire contact pressure to the HMAC layer, and the high-modulus material rapidly disperses the load to the base course and subgrade, avoiding local stress accumulation.

When the smoothness decreases, slight undulations appear on the pavement surface, and the pavement enters a "settlement state" more quickly. The maximum vertical displacement of the HMAC pavement increases from 0.24 mm to 0.33 mm, but the deformation curve remains continuous. This indicates that the HMAC pavement layer can maintain structural stability under local load concentration, reduce creep deformation in concave areas, and alleviate deformation incoordination at joints. It is thus proven that HMAC pavement layers have stronger adaptability to fluctuations in pavement smoothness and can effectively control vertical deformation within a reasonable range even in reconstructed and expanded road sections with poor smoothness.

3.3 Influence of Wheel Pressure on Pavement Deformation Response

As a direct reflection of vehicle load, wheel pressure exhibits a significant positive correlation with pavement vertical deformation. The difference in the deformation resistance advantages of HMAC pavement layers under different wheel pressure conditions is key to evaluating their engineering applicability. This study set three scenarios: low wheel pressure (0.7 MPa, corresponding to a 10-ton load), medium wheel pressure (1.091 MPa, corresponding to a 20-ton load), and high wheel pressure (1.6 MPa, corresponding to a 30-ton load). The pavement smoothness was maintained at Grade A (IRI = 1.8 m/km) and the driving speed at 60 km/h, with the simulation results shown in Figure 8.

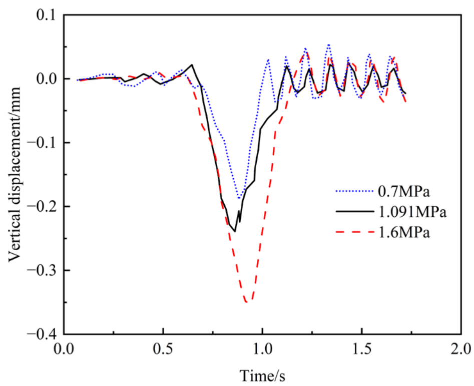


Figure 8: Pavement Deformation Response Under Different Wheel Pressures.

From the absolute value of the curve peak, it can be seen that vertical deformation increases significantly with increasing wheel pressure. When the wheel pressure is 0.7 MPa, the absolute value of the maximum vertical displacement is approximately 0.20 mm. At this time, the load level is low, and the deformation behavior of HMAC is dominated by its high elastic modulus, with the material mainly undergoing elastic deformation. As the wheel pressure increases, the absolute value of the maximum vertical displacement increases to over 0.35 mm, and the curve shows a more obvious "concave" trend during the load action stage. The increase in wheel pressure raises the internal stress level of HMAC, and the contribution of viscoelastic creep begins to emerge, eventually becoming the main component of deformation.

From the perspective of the dynamic response process over time, under continuous load action, the stress of HMAC increases linearly with wheel pressure, while the deformation exhibits a nonlinear response due to the viscoelastic properties of the material. During the unloading and recovery stage, as the wheel gradually moves away from the pavement, the vertical displacement begins to rebound. The curve under the 0.7 MPa condition stabilizes most quickly, while the curve under the 1.6 MPa condition fluctuates for a longer period. This reflects that higher wheel pressure leads to stronger residual stress and viscoelastic hysteresis effect inside HMAC, resulting in a slower deformation recovery process.

3.4 Influence of Driving Speed on Pavement Deformation Response

Asphalt materials exhibit obvious creep under low speeds and are dominated by elasticity under high speeds. Driving speed affects the viscoelastic response of asphalt concrete materials by altering the load action time, thereby changing the vertical deformation law of the pavement. Based on the actual driving scenarios of reconstructed and expanded roads, this study set three speed levels: low speed (40 km/h), medium speed (60 km/h), and high speed (80 km/h). The wheel pressure was maintained at 1.091 MPa and the pavement smoothness at Grade A (IRI = 1.8 m/km), with the simulation results shown in Fig. 9.

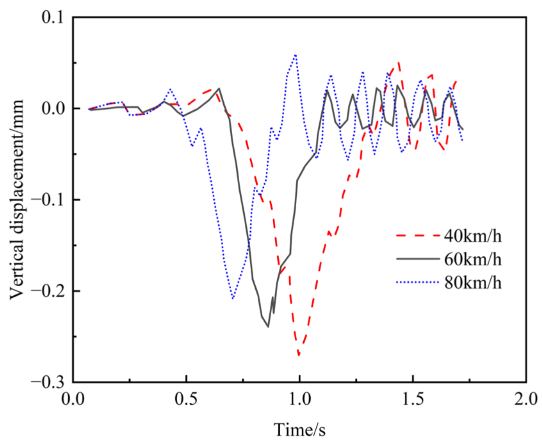


Figure 9: Pavement Deformation Response Under Different Driving Speeds.

As shown in the figure, when the driving speed is 40 km/h, the absolute value of the maximum vertical displacement is approximately 0.28 mm. The deformation curve shows a "deep and continuous concave" feature during the core load action stage, and the deformation recovery process is relatively slow afterward. This is because the wheel acts on the pavement for a longer time at low speeds, leading to a significant viscoelastic creep effect of HMAC, and the viscoelastic deformation accounts for a high proportion of the total deformation. When the driving speed increases, the absolute value of the maximum vertical displacement decreases to 0.22 mm, the "concave degree" of the curve is alleviated, and the deformation recovery speed is significantly accelerated. At this point, the deformation of HMAC is dominated by elastic response, and the proportion of viscoelastic creep is greatly reduced, resulting in a significant decrease in deformation.

Analysis shows that creep dominates deformation under low-speed conditions, while elastic deformation dominates under high-speed conditions. This result verifies the deformation adaptability of HMAC under different driving speed scenarios. For engineering practice, if there are significant speed differences in reconstructed and expanded roads (e.g., both low-speed congested sections and high-speed sections exist), the thickness of the HMAC pavement layer or the content of modified asphalt can be optimized based on the results of this study to further adapt to the deformation requirements of different speed conditions.

4. Conclusions and Prospects

This study analyzed the application effect of HMAC in reconstructed and expanded roads via numerical simulation, with a particular focus on its influence on vehicle passability under the vehicle lane change condition. The results indicate that HMAC can effectively reduce pavement deformation, improve smoothness, and enhance riding comfort, demonstrating excellent mechanical properties and structural stability at joints.

This study systematically analyzed the effects of pavement smoothness, wheel pressure, and driving speed on the vertical displacement response of HMAC pavement layers, leading to the following conclusions: HMAC pavement layers exhibit strong adaptability to fluctuations in pavement smoothness. When pavement smoothness decreases, their high elastic modulus can effectively disperse local load concentration, enabling them to control vertical deformation within a reasonable range even in reconstructed and expanded road sections with poor smoothness. The vertical displacement of HMAC increases with increasing wheel pressure. Under the high wheel pressure condition (overload), the peak vertical displacement of HMAC increases by approximately 40%, indicating that HMAC can maintain good deformation resistance even under heavy or overloaded conditions, providing a reliable structural option for reconstructed and expanded roads to cope with heavy traffic. The vertical displacement of HMAC decreases with increasing driving speed, and the proportion of viscoelastic creep gradually reduces. In low-speed congested sections, HMAC can control deformation accumulation through its low creep characteristics; in high-speed sections, it can reduce instantaneous deformation by virtue of its high elastic modulus, effectively ensuring riding comfort.

Future research can further combine actual engineering cases to verify the durability of HMAC under long-term service conditions, explore its applicability under different climatic and traffic conditions, and expand research on the long-term performance of HMAC under the coupling of multiple factors, so as to provide a more comprehensive theoretical basis for the refined design of HMAC in reconstructed and expanded roads.

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