

Study on the Influence of High Modulus Asphalt Concrete on Highway Culverts

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Abstract: High Modulus Asphalt Concrete (HMM-13) has been widely applied in the reconstruction and expansion projects of highways due to its significantly improved dynamic modulus and resistance to permanent deformation. Aiming at the special mechanical response of the coupling part between pavement and structure in the culvert area, this study adopted the three-dimensional finite element method (Abaqus, C3D8R element) to comparatively analyze the effects of three typical working conditions (vehicle approaching, leaving and passing directly above the culvert) on the stress distribution and vertical displacement characteristics of pavement structure and culvert body under the conditions of HMM-13 overlay and conventional SBS modified asphalt concrete (Normal SBS) overlay.

Keywords: High Modulus Asphalt Concrete; Culvert; Finite element analysis; Stress distribution

1. Introduction

With the rapid development of China's highway network, many early-built highways have entered the stage of reconstruction and expansion, facing problems such as the sharp increase in traffic volume, frequent pavement diseases and insufficient durability [1-3]. As an advanced pavement material, High Modulus Asphalt Concrete (HMM-13) achieves a modulus 1.5 to 2 times that of conventional asphalt concrete through high modulus modifiers or special gradation design, which significantly improves the rutting resistance, fatigue durability and bearing capacity, and thus has been widely used in reconstruction and expansion projects [4-6]. Its advantages lie in enhancing the overall stiffness of the pavement, effectively inhibiting deformation, reducing the pavement thickness and optimizing economic efficiency, which are far superior to the flexible characteristics of conventional asphalt concrete [7].



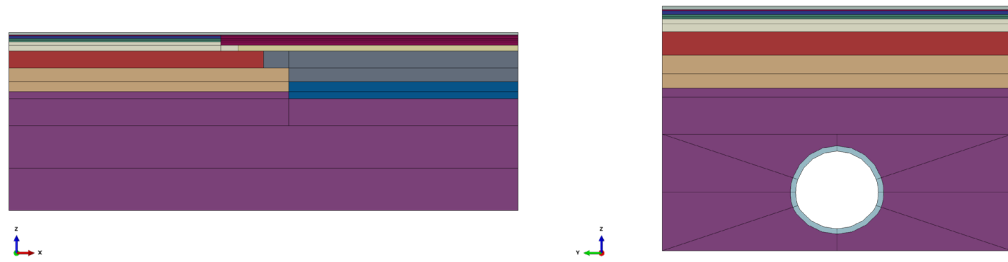
Figure 1: Construction Site of Highway Reconstruction and Expansion Project.

As a drainage channel under the pavement, the mechanical response of culverts to the vehicle loads passing through is affected by the upper pavement layer. Although conventional asphalt concrete with low elastic modulus has good deformation coordination, it is prone to rutting and cracking, leading to stress concentration and uneven settlement on the top of culverts [8-9]. The high modulus pavement layer increases the stiffness of the upper pavement structure and changes the load diffusion path, which may increase the local stress and shear force. However, its advantage of high bearing capacity is conducive to the uniform distribution of load and the reduction of overall settlement, potentially lowering the risk of culvert diseases [10]. Existing studies have mostly focused on the advantages of HMM materials and the overall behavior of pavements, with insufficient comparative analysis on the mechanical response of culvert structures, which restricts the optimization of design [11-12].

Based on finite element simulation, this paper analyzes the stress distribution and deformation of road structure and culvert when vehicles approach, pass through and leave the upper pavement of culvert under the pavements of high modulus asphalt concrete and conventional asphalt concrete, so as to explore the application of high modulus asphalt concrete in the reconstruction and expansion of highway engineering.

2. Establishment of the Numerical Model

In this paper, a 3×3×6 m highway section with a culvert passing through the subgrade was selected for modeling. The section is mainly composed of the UPAVE-10 layer, asphalt cement concrete layer (conventional asphalt concrete layer/high modulus asphalt concrete layer), SMA-13 layer, AC-16 layer, AC-30 layer, AM-30 layer, cement-stabilized macadam layer, low-dosage cement concrete layer and subgrade layer. The different layers of the road were constrained by bonding. Based on the symmetry of the geometric entity, symmetric constraints were applied to the four sides of the road model, and gravity load was applied to the model. The C3D8R element was adopted, and the simulation was carried out through the static module of Abaqus.



(a) Cross-sectional view of road structure

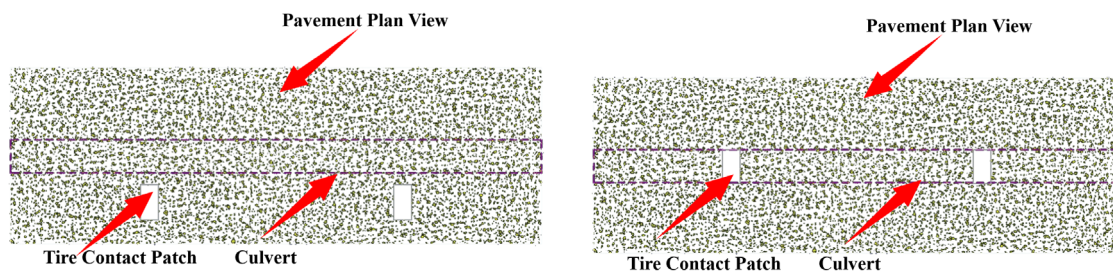
(b) Cross-sectional view of highway culvert

Figure 2: Numerical Geometric Model.

The partial parameters of the pavement structure are shown in Table 1.

Table 1 Partial Parameters of Pavement Structure.

Material Name	Elastic Modulus (MPa)	Poisson's Ratio
HMM-13	3000	0.25
Normal SBS	1700	0.35
AC-16	1600	0.35
AC-30	1500	0.35
AM-30	1400	0.35
SMA-13	2000	0.25
Sup-25	1800	0.25



(a) Schematic diagram of loading during vehicle approaching/leaving the culvert

(b) Schematic diagram of loading during vehicle passing through the culvert

Figure 3: Schematic Diagram of Pavement Loading.

3. Results and Analysis

Taking the central section of the culvert as the analysis datum plane, the distribution characteristics of the stress field and displacement field of the pavement structure and culvert body under two typical loading conditions (vehicle approaching/leaving stage and passing directly above stage) were systematically investigated. The analysis focused on comparing the differences between two surface layer schemes, namely conventional SBS modified asphalt concrete (Normal SBS, $E \approx 1700$ MPa) and high modulus asphalt concrete (HMM-13, $E = 3000$ MPa), to reveal the influence law of the improvement of surface layer stiffness on the load transfer path, stress concentration degree and deformation control effect.

3.1 Influence of Different Asphalt Concrete Overlays on Road Structure

When Normal SBS was used as the main asphalt surface layer, the disturbance of the vehicle approaching/leaving stage on the pavement structure above the culvert was relatively limited, and the peak values of stress and displacement were mainly concentrated near the wheel load action area; however, when the wheel load acted directly above the culvert, obvious stress concentration and deformation amplification phenomena appeared in the central section of the culvert. The calculation results showed that compared with the approaching/leaving stage, the maximum principal stress increased by about 37% and the maximum vertical displacement increased by about 32% under the direct upper loading condition.

The right-side area of the subgrade showed a certain lateral load diffusion capacity due to the laying of a thicker Normal SBS layer (replacing part of the low-modulus structural layer), which was conducive to alleviating the direct impact of local concentrated load on the lower structure and restraining the development of the peak value of vertical displacement to a certain extent. However, due to the relatively low modulus of Normal SBS, its overall stiffness was insufficient to significantly change the vertical transfer gradient of load, resulting in an obvious trend of stress concentration and uneven settlement in the area directly above the culvert.

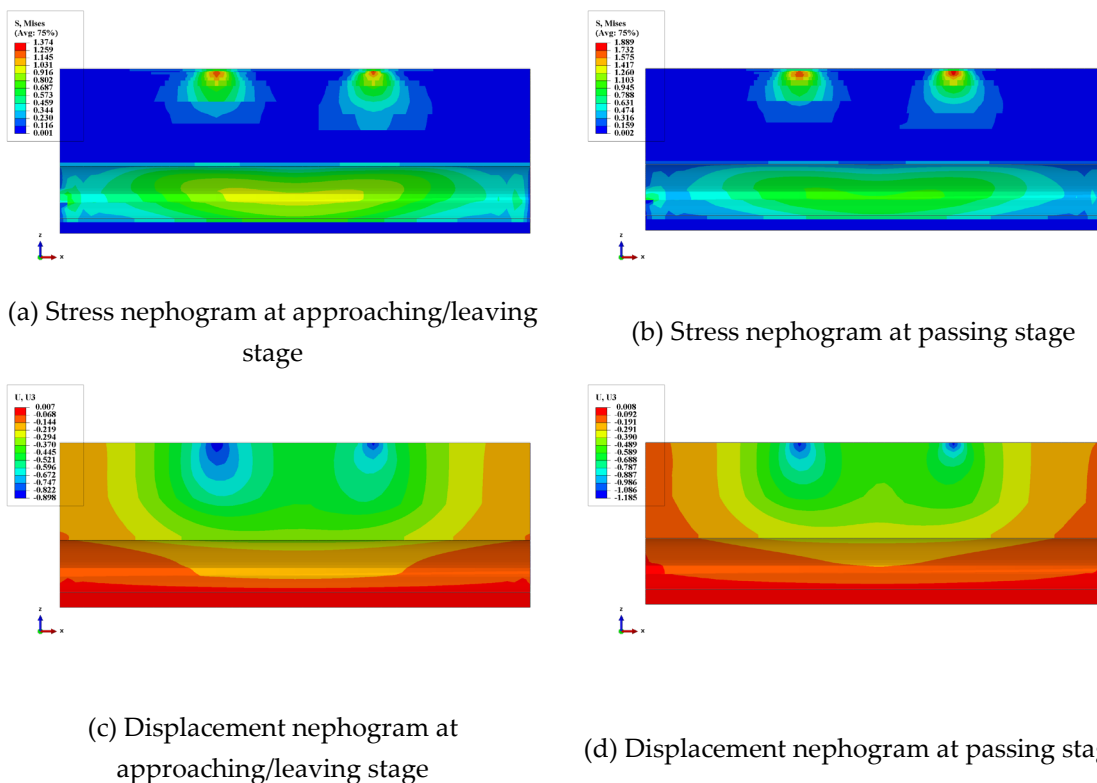


Figure 4: Stress and Displacement Distribution Nephograms of Normal SBS.

After replacing Normal SBS with HMM-13 (high modulus asphalt concrete) as the main surface layer, the distribution patterns of stress and displacement under the three working conditions were basically consistent with those of Normal SBS, but the peak response was significantly improved. When the wheel load acted directly above the culvert, the increase rate of the maximum principal stress of the central section decreased to about 32% (a relative decrease of about 13.5% compared with Normal SBS), and the increase rate of the maximum vertical displacement decreased to about 29% (a

relative decrease of about 9.4%). The disturbance amplitude and change rate of the pavement structure during the whole loading process were significantly smaller than those of the Normal SBS scheme.

It is particularly noteworthy that the right-side area of the subgrade had a significantly enhanced lateral diffusion capacity for concentrated load due to the adoption of a higher stiffness and thicker HMM-13 layer. The higher modulus made the load transfer more in the horizontal direction, reduced the vertical stress gradient, effectively inhibited the occurrence of local peak vertical displacement, and significantly improved the deformation coordination. This indicates that the improvement of surface layer stiffness not only reduces the degree of stress concentration in the area directly above the culvert, but also improves the uniformity of the overall mechanical response of the overlying pavement structure in the entire culvert area by optimizing the load diffusion path.

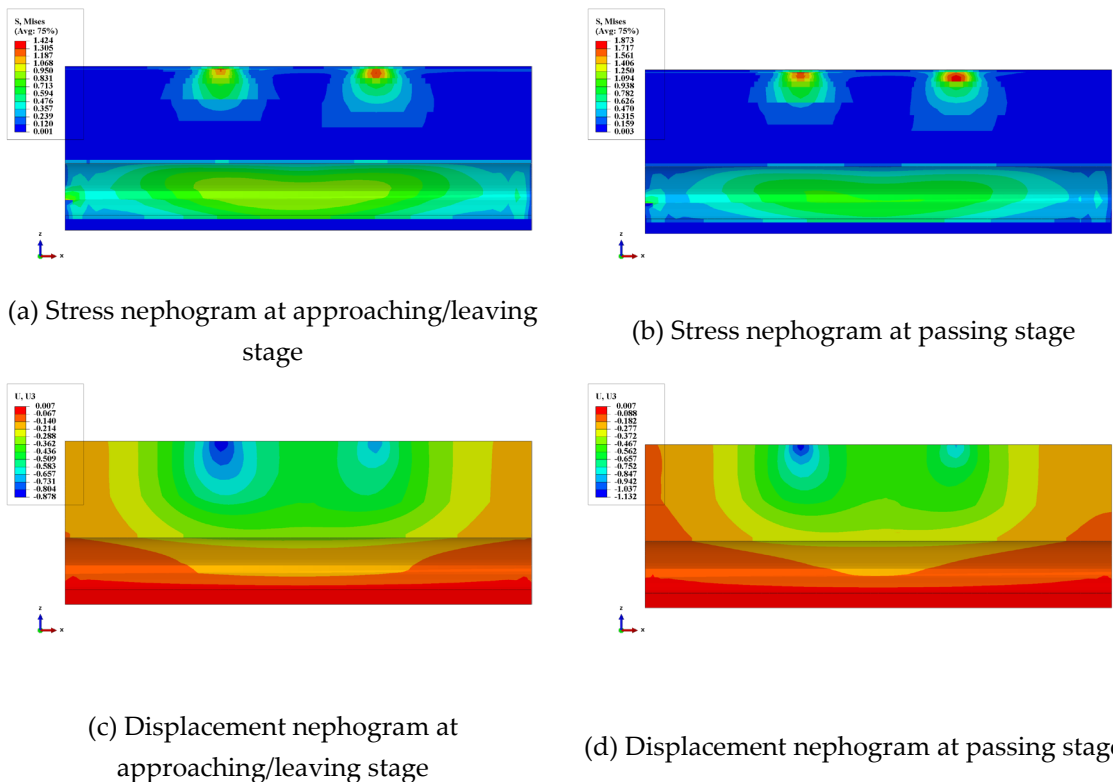


Figure 5: Stress and Displacement Distribution Nephograms of HMM-13.

3.2 Influence of Different Asphalt Concrete Overlays on Culvert Structure

This paper further analyzed the response of culvert structures to different loads.

When Normal SBS and HMM-13 were used as the pavement layers respectively, the vertical displacement responses of the culvert structure to the two loading conditions are illustrated in Fig. 6.

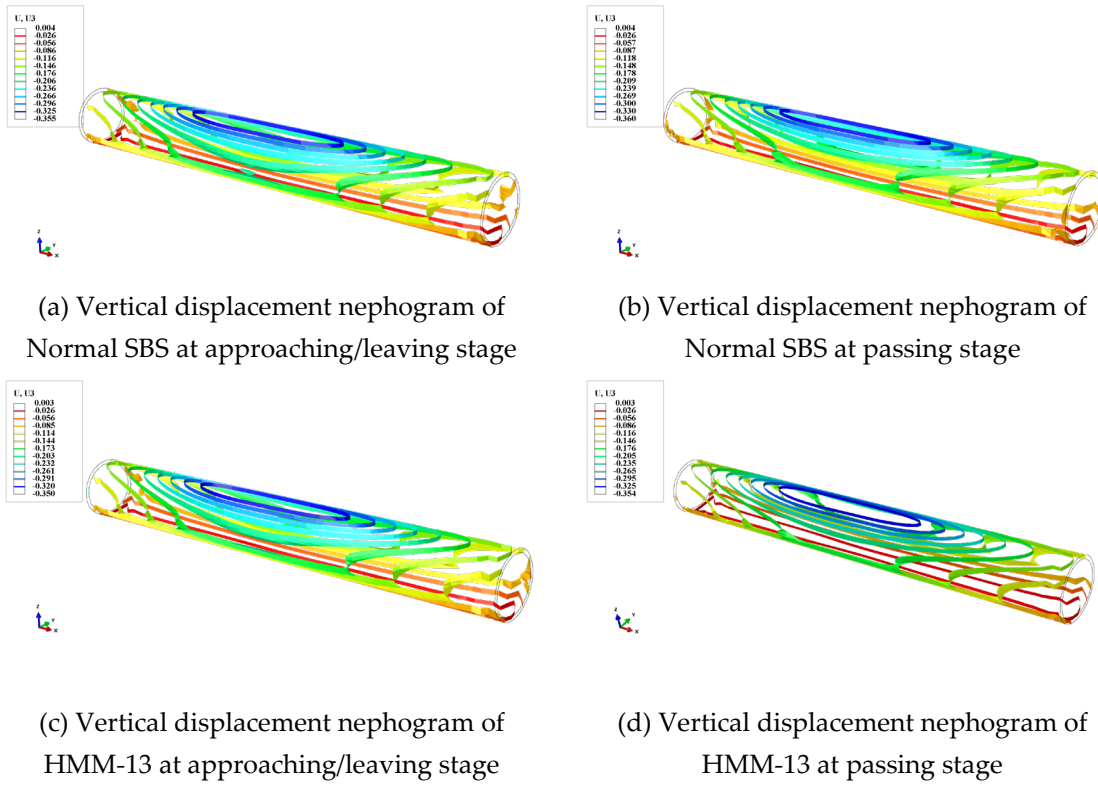
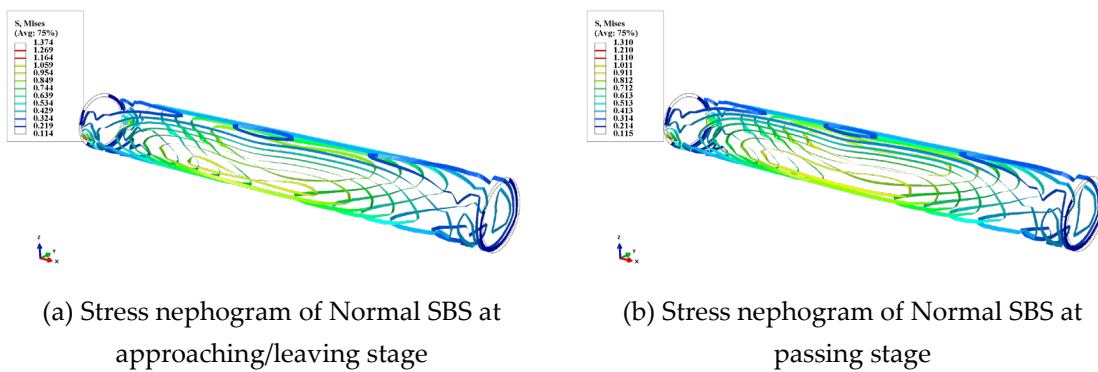


Figure 6: Vertical Displacement Distribution Nephograms of Culvert.

The vertical displacement cloud diagrams of the culvert body show that under the two surface layer conditions, the overall displacement level of the HMM-13 scheme was slightly lower than that of the Normal SBS scheme, especially when the wheel load passed directly above, the peak displacement control was more stable and the change of deformation gradient was relatively gentle. Although the absolute displacement difference between the two schemes was not significant, the HMM-13 surface layer made the settlement distribution on the top of the culvert more uniform and reduced the risk of local uneven settlement. This is mainly due to the fact that the high modulus surface layer improves the overall stiffness of the pavement structure and reduces the concentrated transfer effect of load to the culvert top slab.

When Normal SBS and HMM-13 were used as the pavement layers respectively, the load responses of the culvert to the two loading conditions are presented in Fig. 7.



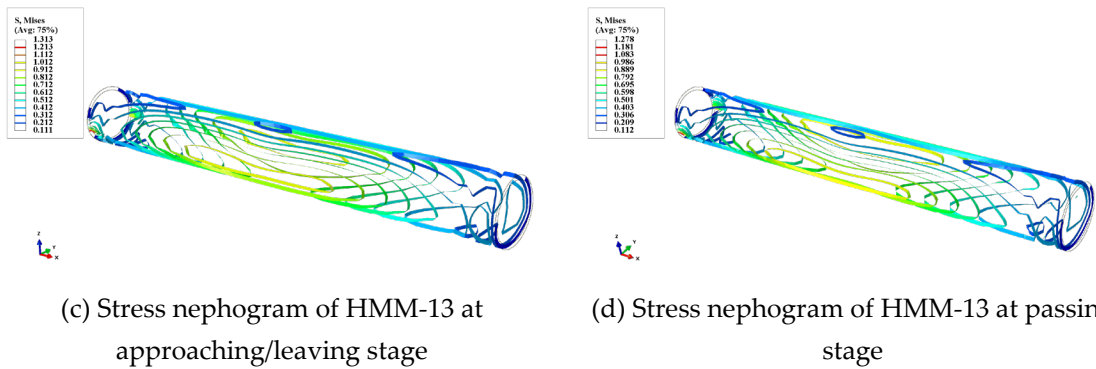


Figure 7: Stress Distribution Nephograms of Culvert.

The stress distribution cloud diagrams of the culvert show that the difference in the principal stress response of the culvert structure was more significant. Whether under the approaching/leaving working condition or the direct upper passing working condition, the maximum and minimum principal stress levels borne by the culvert structure with the HMM-13 surface layer were significantly lower than those with the Normal SBS scheme. This indicates that the high modulus surface layer effectively reduces the peak load intensity transmitted to the culvert.

More importantly, the relative difference of the maximum principal stress of the culvert between the two extreme working conditions (approaching/leaving and passing directly above) was 4.6% under the Normal SBS scheme, while it decreased to 2.6% under the HMM-13 scheme. This result clearly reflects that the HMM-13 surface layer makes the load transfer stiffness at the pavement-culvert interface higher and the fluctuation range smaller, the stress change gradient tends to be gentle, and the load transfer process is more stable and uniform.

From the perspective of mechanical mechanism, by significantly improving the overall stiffness of the pavement structure, high modulus asphalt concrete changes the traditional load diffusion mode of flexible pavement of "concentrated downward transfer" to a better path of "lateral dispersion + vertical homogenization", thus effectively alleviating the local stress concentration on the top of the culvert, reducing the cumulative rate of structural fatigue damage, and having positive significance for improving the long-term service performance of the culvert.

4. Conclusion

Compared with the conventional SBS modified asphalt concrete overlay, the High Modulus Asphalt Concrete (HMM-13) overlay can effectively improve the mechanical response characteristics of the pavement structure in the culvert area, which is mainly manifested in that the increase rate of the maximum principal stress of the central section of the culvert is reduced by about 5 percentage points and the increase rate of the maximum vertical displacement is reduced by about 3 percentage points when the vehicle wheel load passes directly above. At the same time, it exhibits better concentrated load diffusion and deformation inhibition capacity in the edge area of the subgrade.

In terms of the own response of the culvert structure, the HMM-13 overlay reduces both the maximum and minimum stress levels borne by the culvert, and the relative difference of the maximum stress between the two typical working conditions (approaching/leaving and passing directly above) decreases from 4.6% to 2.6%, indicating that the load transfer process is more uniform and stable, which is conducive to reducing the risks of local stress concentration and long-term cumulative damage on the top of the culvert.

Comprehensive analysis shows that high modulus asphalt concrete has good applicability and potential economic-durability advantages in the culvert area of highway reconstruction and expansion projects by significantly improving the overall stiffness and load diffusion capacity of the pavement, and it can be used as an important technical option for the optimization of pavement structure in the culvert area.

References

- [1] Tan, Zhifei, et al. "Numerical study of the aggregate contact effect on the complex modulus of asphalt concrete." *Materials & Design* 213 (2022): 110342.
- [2] Tan, Zhifei, et al. "Numerical modeling of the mechanical response of asphalt concrete in tension and compression." *Mechanics of materials* 187 (2023): 104823.
- [3] Si, Chundi, et al. "Dynamic response analysis of rutting resistance performance of high modulus asphalt concrete pavement." *Applied Sciences* 8.12 (2018): 2701.
- [4] Wang, Wentao, and Linbing Wang. "Review on design, characterization, and prediction of performance for asphalt materials and asphalt pavement using multi-scale numerical simulation." *Materials* 17.4 (2024): 778.
- [5] Hajikarimi, Pouria, et al. "Heterogeneous visco-hyperelastic numerical modelling of crumb rubber-modified asphalt binders." *International Journal of Pavement Engineering* 23.5 (2022): 1500-1511.
- [6] Deng, Yong, et al. "Numerical modelling of rutting performance of asphalt concrete pavement containing phase change material." *Engineering with Computers* 39.2 (2023): 1167-1182.
- [7] Tehrani, F. Fakhari, et al. "Heterogeneous numerical modeling of asphalt concrete through use of a biphasic approach: Porous matrix/inclusions." *Computational Materials Science* 69 (2013): 186-196.
- [8] Karimi, Mohammad M., et al. "Development of a stress-mode sensitive viscoelastic constitutive relationship for asphalt concrete: experimental and numerical modeling." *Mechanics of Time-Dependent Materials* 21.3 (2017): 383-417.
- [9] Wang, Houzhi, et al. "Numerical simulation on reflective cracking behavior of asphalt pavement." *Applied Sciences* 11.17 (2021): 7990.
- [10] Gao, Huan, et al. "Mechanical properties of fiber-reinforced asphalt concrete: Finite element simulation and experimental study." *e-Polymers* 21.1 (2021): 533-548.
- [11] Liu, Pengfei, et al. "Numerical simulation of crack propagation in flexible asphalt pavements based on cohesive zone model developed from asphalt mixtures." *Materials* 12.8 (2019): 1278.
- [12] Chen, Jiaqi, Xu Ouyang, and Xiao Sun. "Numerical investigation of asphalt concrete fracture based on heterogeneous structure and cohesive zone model." *Applied Sciences* 12.21 (2022): 11150.