

Mechanical response-based structural optimisation of prefabricated plastic pavement module

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ABSTRACT: This study investigated the mechanical responses of a semi-rigid base pavement with asphalt concrete and prefabricated plastic modules, aiming to optimise the structural design of prefabricated modules. Three types of structural forms were designed and a dynamic finite element (FE) modelling with moving loads was conducted. Different types of stress and strain were compared to highlight the differences of various types of modular structural designs. Results indicate that the stress and strain for the prefabricated plastic module are higher than those in the asphalt concrete layer due to the hollow structure and its relatively lower modulus. The stress distribution and concentration can be optimised by adding supports within the hollow structure. The mechanical responses of the layers below surface layer remain unchanged after replacing asphalt concrete with prefabricated plastic modules. According to this case study, the prefabricated plastic pavement modules would not experience strength failure.

1 INTRODUCTION

Forwarding to a net-zero road infrastructure is a worldwide strategic goal, including the implementations of low-carbon materials, intelligent construction and in-situ testing, and digital twin-enabled maintenance decision making. Among those solutions, recycling and reusing waste plastics in asphalt pavement constructions are widely used practices that have produced many successful applications. There are two major methods for using waste plastics in asphalt pavements: wet process and dry process (You *et al.* 2022). The former involves mixing waste plastics with bitumen to form a new type of modified bitumen, while the latter utilises waste plastics as a replacement for a portion of fine aggregates. As can be seen, the waste plastics are simply mixed with either the bitumen or asphalt concretes without consideration of their interaction mechanisms. Other methods include mixing the waste plastic-derived components with bitumen after chemical treatments (e.g., pyrolysis), in an attempt to stabilise the waste plastic-bitumen mixture (Abdy *et al.* 2023). The main challenge of current practices for using waste plastics in asphalt pavements is that the waste plastics are used as either bitumen modifier or fine aggregate replacement, thereby limiting their applications in large dosages. Thus, finding ways to significantly increase the amount of waste plastics used in road constructions presents a challenge and requires innovative approaches beyond material processing.

In 2018, the world's first plastic road was opened in the Netherlands (Wavin 2018). It is a cycle path entirely made with recycled plastic-based modular

components. This is a completely different approach compared to the current practices in road engineering; however, its material information and structural design are inaccessible which makes further research difficult. More importantly, whether this new type of prefabricated plastic pavement can be used in other application scenarios (e.g., motorway and urban road) is still unknown as its bearing capacity needs further investigations. Prefabricated pavement is not a new technology and many applications have been conducted successfully, especially for concrete pavements (Guo *et al.* 2024). Regarding this type of pavement structure, attention should be given to the cross-section profile optimisation, joint design, and interface bonding characterisation. Compared to asphalt concretes, the waste plastic-extruded solid mixture is relatively soft with a typical stiffness from 600 MPa to 3500 MPa. However, it is worth considering whether the overall strength of prefabricated plastic pavement modules can be improved to meet the normal road design criteria by optimising its structural form. This concept has the potential to be a promising solution for effectively reusing waste plastics in pavement engineering.

In summary, this paper is the first attempt to optimise the structural forms of prefabricated plastic pavement modules based on their mechanical responses. This paper is organised as follows. The next section details the three different structural designs of prefabricated plastic pavement modules and their material properties. The following section presents the governing equations and model information used in the finite element (FE) modelling. Finally, the comparisons of mechanical responses of different

structural forms are presented, and conclusions and recommendations are summarised in the last section.

2 STRUCTURAL DESIGN AND MATERIAL PROPERTY

Three types of structural forms were designed for the following comparative and optimisation study, considering their bearing capacity and manufacturing feasibility. Figure 1 shows the cross-section profiles and 3D structural forms of these hollow modules, including the box girder (Type I), box girder with cylinder support (Type II), and box girder with cone support (Type III). Besides, a typical asphalt pavement with a semi-rigid base was selected as the benchmark model. The asphalt concrete (AC) was then replaced by the prefabricated plastic modules in the FE modelling used for the following sections. Table 1 shows the pavement structural and material information.

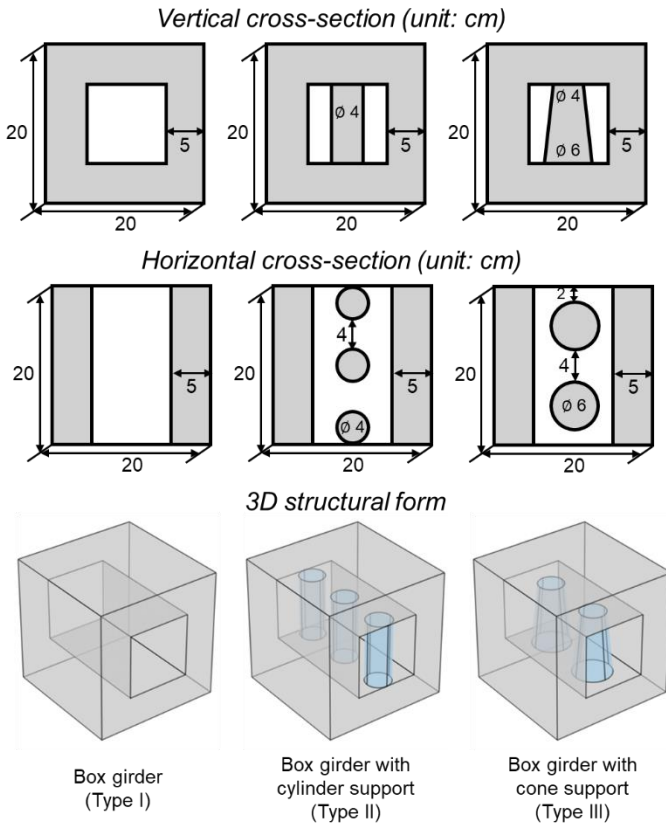


Figure 1. Structural design of prefabricated plastic modules. Table 1. Structural and material information (adapted from (Assogba *et al.* 2021)).

Layer	Material	Thickness (cm)	E (MPa)	ν	ρ (kg/m ³)
Surface	AC	20	7000	0.3	2250
	PPM		2000	0.4	1230
Base	CTM	40	15000	0.25	2350
Subbase	CTS	20	4000	0.25	2300
Subgrade	Soil	200	60	0.4	2400

Note: AC refers to asphalt concrete; PPM refers to prefabricated plastic module; CTM refers to cement treated macadam; CTS refers to cement treated soil.

3 FINITE ELEMENT MODELLING

This work employed a single tire moving load as the traction boundary condition. The contact pressure was set as 0.7 MPa and the vehicle speed was set as 20 m/s. The tire-road contact area was simplified as a square with a 20 cm side length. Currently, all the material models were assumed to be isotropic linear elastic. Figure 2 shows the model geometry and boundary conditions.

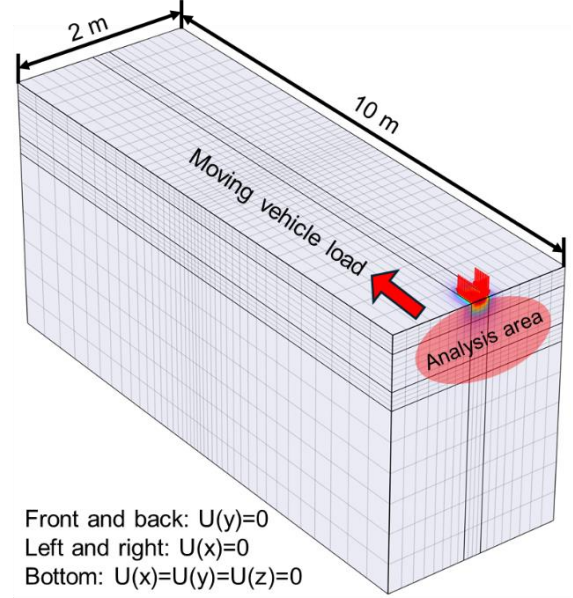


Figure 2. Pavement FE model.

The following presents the governing equations for the initial-boundary value problem (IBVP) in the pavement response FE modelling. It should be noted that Rayleigh damping is used for each layer of material in this dynamic analysis, and the coefficients were selected as 1.04 (α_{dM}) and 5.59e-3 (β_{dK}). More details regarding the pavement FE modelling can refer to the authors' previous work (Zhang *et al.* 2024).

Equilibrium equation:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} + \alpha_{dM} \rho \frac{\partial \mathbf{u}}{\partial t} = \nabla \cdot (\boldsymbol{\sigma} + \beta_{dK} \frac{\partial \boldsymbol{\sigma}}{\partial t}) + \mathbf{F}_V \quad (1)$$

where ρ is the density; t is the loading time; $\mathbf{u}$ is the displacement vector; $\boldsymbol{\sigma}$ is the second-order stress tensor, $\mathbf{F}_V$ is the body force; and α_{dM} and β_{dK} are the coefficients of Rayleigh damping.

Constitutive equation:

$$\boldsymbol{\sigma} = \mathbf{C} : \boldsymbol{\varepsilon} \quad (2)$$

where $\boldsymbol{\varepsilon}$ is the second-order strain tensor; and $\mathbf{C}$ is the fourth-order stiffness matrix.

Kinematic equation:

$$\boldsymbol{\varepsilon} = \frac{1}{2} [(\nabla \mathbf{u})^T + \nabla \mathbf{u}] \quad (3)$$

4 RESULTS AND DISCUSSION

In this section, the mechanical analysis is conducted on the central cross-section when the vehicle load precisely aligns with the top of the prefabricated plastic pavement module.

First, the von Mises stress distribution and magnitude are presented in Figure 3 to compare the overall bearing capacity for the semi-rigid base pavement structures with asphalt concrete and three types of plastic modules. As can be seen, the hollow structure of prefabricated pavement module hinders the stress dispersion from the road surface to the underlying layers and thus, the maximum magnitude of von Mises stress is almost twice that of normal asphalt pavements and occurs at the joints of two modules. However, this adverse stress distribution can be optimised by adding supports within the hollow structures, as shown in the results of Type II and Type III modules. The highest stress is localised at the edges of joint, and the overall stress dramatically decreases compared to the results of Type I structure. Further, the maximum stress is still much lower than the typical strength (higher than 2 MPa) of solid plastics and it is unlikely to result in strength failure.

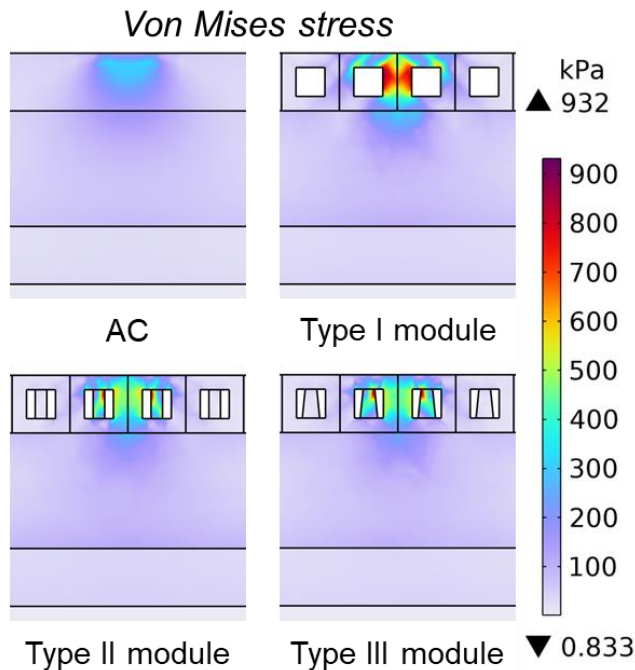


Figure 3. Comparison of von Mises stress.

For a typical semi-rigid base pavement structure, the transition of compression-tension usually occurs at the semi-rigid base due to its relatively greater thickness and modulus. Thus, the mechanical analysis should focus on the vertical stress of the AC layer and the tensile stress of the semi-rigid base. Figure 4 shows the comparison of vertical stress. As can be seen, the Type I structure has the highest vertical stress distributed through the joint of two modules. With the cylinder and cone supports, the vertical stress of Type II and Type III structures is similar to

the traditional asphalt concrete layer, although there are still some stress concentrations at the sharp edges.

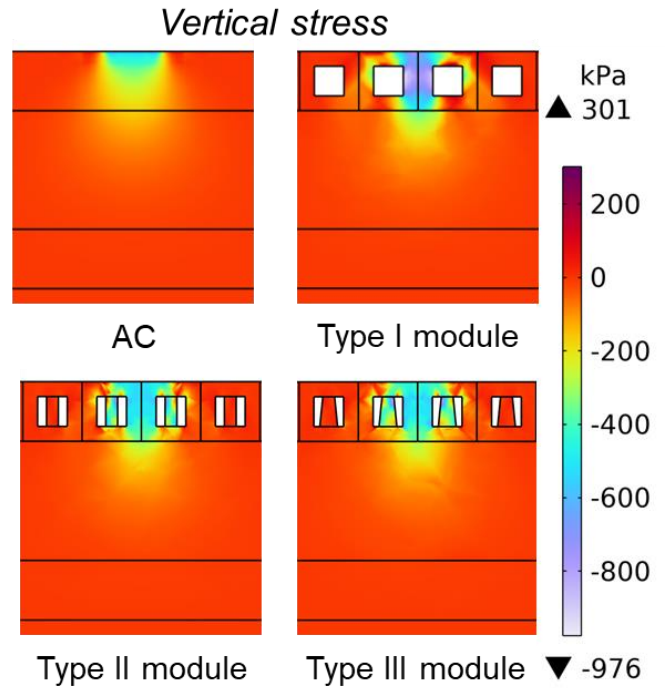


Figure 4. Comparison of vertical stress.

Figure 5 shows the comparison of the tensile stress along the moving load direction. Compared to the traditional pavement structure, the tensile stress at the bottom of the base layer of the Type I and Type II structures is relatively higher, while the Type III structure shows a similar tensile stress value when compared to the asphalt concrete structure. Moreover, higher tensile stress is found at the bottom of the top half-structure for those prefabricated modules, particularly for Type I structure. This phenomenon arises due to the bending characteristics of beam structures. The modules with supports can optimise this phenomenon by localising the high tensile stress at the joints.

In addition to analysing these stress distributions, Figure 6 shows the comparison of the tensile strain along the moving load direction. The tensile strains for the three types of plastic modules are much higher than those in the asphalt concrete due to their relatively lower modulus. The structures of Type II and Type III modules can reduce the areas with large deformations. Although the maximum strain under a single vehicle load would not reach the failure strain of plastics, whether or not there would be fatigue failure requires further investigations.

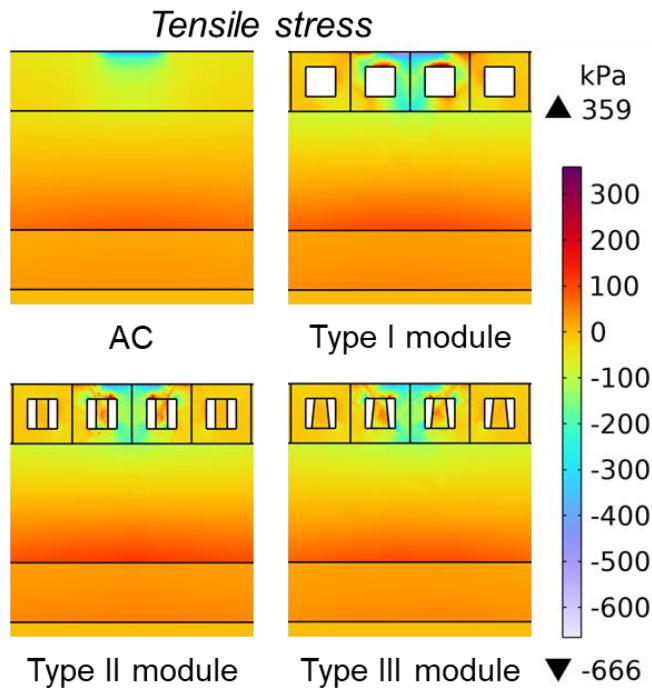


Figure 5. Comparison of tensile stress.

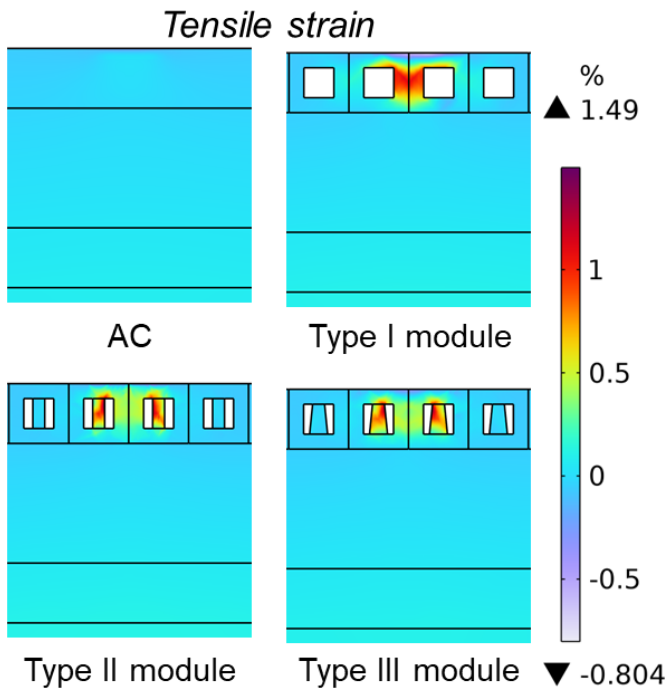


Figure 6. Comparison of tensile strain.

5 CONCLUSIONS AND RECOMMENDATIONS

This paper compares the mechanical responses of different types of prefabricated plastic pavement modules with traditional asphalt pavement structures, aiming to optimise their structural design. The major conclusions are as follows:

- The stress and strain in the prefabricated plastic module are higher than those in the asphalt concrete layer due to the hollow structure and its relatively lower modulus.

- Replacing asphalt concrete with the prefabricated plastic module would not affect the mechanical responses of the layers below the surface layer.
- The stress distribution can be optimised by adding supports within the hollow structure.
- The prefabricated plastic pavement modules are unlikely to experience strength failure according to this case study.

More structural designs with different types of supports are needed in future work. In addition, a more realistic material model (e.g., thermal-elasto-plastic) is required, along with the model parameter calibration. In particular, the effects of thermal stress need to be investigated. More importantly, the screening of joint materials and designs is critical to further optimising the stress distribution and dispersion in the prefabricated plastic pavement modules.

6 ACKNOWLEDGMENTS

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REFERENCES

- Abdy, C., Zhang, Y., Wang, J., Cheng, Y., Artamendi, I., and Allen, B., 2023. Investigation of high-density polyethylene pyrolyzed wax for asphalt binder modification: Mechanism, thermal properties, and ageing performance. *Journal of Cleaner Production*, 405.
- Assogba, O.C., Tan, Y., Sun, Z., Lushinga, N., and Bin, Z., 2021. Effect of vehicle speed and overload on dynamic response of semi-rigid base asphalt pavement. *Road Materials and Pavement Design*, 22 (3), 572–602.
- Guo, J., Chan, T.M., and Wang, Y., 2024. Precast concrete pavement applications, design and joint load transfer characteristics. *Structures*, 69.
- Wavin, 2018. The world's first plastic road opens in the Netherlands [online]. Available from: <https://blog.wavin.com/en-gb/plastic-road-launch> [Accessed 28 Nov 2024].
- You, L., Long, Z., You, Z., Ge, D., Yang, X., Xu, F., Hashemi, M., and Diab, A., 2022. Review of recycling waste plastics in asphalt paving materials. *Journal of Traffic and Transportation Engineering (English Edition)*, 9 (5), 742–764.
- Zhang, H., Airey, G., and Zhang, Y., 2024. Temporal Homogenization Modeling of Viscoelastic Asphalt Concretes and Pavement Structures under Large Numbers of Load Cycles. *Journal of Engineering Mechanics*, 150 (11).