*Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)*
*Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5*
*https://doi.org/10.53243/ICSMGE2026-1101*

# Thermo-mechanical response of hydronic asphalt pavement under heating and cooling operations

**Taher Ghalandari,** Cedric Vuye
*Department of Construction Engineering, Sustainable Pavements and Asphalt Research (SuPAR), University of Antwerp, Antwerp, Belgium, Taher.Ghalandari@uantwerpen.be*

Anh Minh Tang, Jean-Michel Pereira
*Navier Laboratory, ENPC, Institut Polytechnique de Paris, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France*

ABSTRACT: The hydronic asphalt pavement (HAP) system is an innovative component of sustainable infrastructure, designed to harness both solar and shallow geothermal energy. With an embedded heat exchange layer within the asphalt pavement, the fluid circulates through the pipes, effectively cooling the asphalt while harvesting low-temperature solar energy. Despite challenges associated with embedding pipes, such as potential reductions in the stiffness of asphalt layers, HAPs effectively regulate extreme pavement temperatures, reducing the risk of pavement distress. This study presents an integrated thermo-mechanical finite element (FE) modelling framework for assessing the structural and thermal performance of HAP systems. The approach combines long-term thermal field data with experimental rutting performance tests to quantify the impact of seasonal heat extraction on pavement behavior. The results of field-scale experimental cooling tests demonstrated that active cooling of the HAP section eliminated mid-depth temperatures exceeding 40 °C during critical traffic periods, while the reference section exceeded this threshold for approximately 40 % of the time during daytime. These reductions in pavement temperature and temperature gradients provide essential input for thermo-mechanical analysis, enabling the calibrated FE model to simulate rutting performance under realistic operational scenarios. For the mechanical modelling, creep power-law parameters were first calibrated using wheel-tracking tests on a reference specimen, followed by model extension to represent the HAP configuration. The FE predictions showed good agreement with experimental measurements, with mean absolute errors of 0.61 mm for the reference specimen and 0.45 mm for the HAP specimen, validating the proposed modelling framework. The results indicate that HAP systems can substantially reduce the thermal component of rutting susceptibility by maintaining pavement temperatures below critical thresholds during peak traffic hours.

KEYWORDS: Asphalt pavement, Finite element method, rutting, hydronic asphalt pavement, creep.

## 1 INTRODUCTION

Hydronic asphalt pavement (HAP) systems utilize the high solar absorptivity of asphalt surfaces to harvest thermal energy by circulation of fluid through embedded pipes within the pavement. Owing to the widespread availability of asphalt in roads, parking areas, airports aprons, and bicycle paths, these thermo-active structures offer significant potential for large-scale implementation. Depending on the season, HAPs can be operated to harvest renewable energy during warm periods or to maintain ice- and snow-free surfaces in winter (Ghalandari et al., 2021b). As a result of heat extraction in summer, HAPs reduce both surface and profile pavement temperature, thereby helping to mitigate pavement rutting distress (Ghalandari et al., 2023) and decrease urban heat island effect in built environments (Mallick et al., 2009a).

Although the application of HAPs can reduce the temperature gradient through the pavement depth and thereby extend service life (Mallick et al., 2009b; Dakessian et al., 2016), the presence of embedded pipes disturbs the structural uniformity, potentially leading to reduced compaction quality and stress concentrations around the pipes (Zhu et al., 2021). Recent investigations into their structural performance under various loading conditions have indicated that temperature-induced loads can have a greater influence on the structural response than static vehicular loads (Zhou et al., 2021).

It is essential to ensure that the embedment of pipes within asphalt pavements does not compromise structural performance and that any potential risks of damage remain within acceptable limits. Accordingly, the development of a structural modelling framework is crucial for evaluating the long-term effects of heating and cooling in HAP systems on structural responses, such as rutting behaviour. This study addresses this research gap by proposing a thermo-mechanical modelling framework for thermo-active roads. The approach integrates a structural model, calibrated using rutting performance tests conducted with a wheel-tracking device, with long-term thermal data obtained from field measurements.

## 2 THERMAL RESPONSE OF THE HAP SYSTEM UNDER COOLING OPERATION

Full-scale cooling tests for this section were conducted on an experimental HAP system with a reference section (without pipes) under identical climatic conditions. The embedded and installed sensors measured the temperature of asphalt at the surface and mid-depth of pavement, and air temperature continuously between 10 and 14 June 2021. The pipe length within the HAP section was 50 m, with a flow rate of 4 L/min (i.e., turbulent flow). The average supply temperature to the thermo-active road system was 16.0 ± 1.7 °C, while the mean ambient air temperature during the test period was 19.17 °C ± 5.32 (Figure 1). Activating the thermo-active road system for heat harvesting resulted in a measurable reduction in both the surface and profile temperatures of the asphalt pavement (Ghalandari et al., 2022). Figure 1 compares the surface and mid-depth asphalt temperatures for the reference section and the HAP section.

During operation, the HAP mid-depth temperature was on average 8.73 °C lower than the reference, with a maximum observed reduction of 15.08 °C. The peak mid-depth temperature in the HAP was 33.3 °C, compared with 47.6 °C for the reference section, demonstrating the system's effectiveness in alleviating the high-temperature experience of pavement. The cooling operation also reduced vertical thermal gradients between the surface and mid-depth. For the reference section, the average gradient was only 1.46 °C, whereas the HAP indicated a higher mean gradient of 10.19 °C (maximum 20.5 °C) due to active heat harvesting and cooling at depth. These gradients are particularly relevant for thermal and mechanical performance, as they influence distress such as rutting and interface shear stresses.

Analysis of the mid-depth temperatures during the cooling test shows that operating HAP can eliminate the peak temperatures experienced by the pavement and consequently the rutting potential of the structure. Using a 40 °C threshold, the reference section exceeded this limit for almost 20.0 % of the total operating hours. Restricting the analysis to 10:00–22:00 hours, when traffic-induced stresses seem most critical, this high-temperature exposure represented 39.8 % of the daytime period. In contrast, the HAP section under active cooling remained entirely below 40 °C at mid-depth throughout the test. By eliminating high-temperature exposure at this structural layer during peak traffic hours, the HAP system substantially reduces the thermal component of rutting susceptibility.

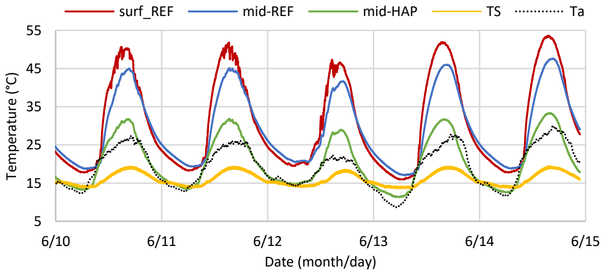

Figure 1. Cooling experiments in reference section (REF) and HAP system; TS = supply temperature, Ta = ambient air temperature.

Research studies reported that test temperature has the strongest influence on rut depth, alongside asphalt mixture type and binder replacement ratio (Majidifard et al., 2021). Their findings indicate that reducing test temperature by 6 °C (from 64 °C to 58 °C) and by 12 °C (from 64 °C to 52 °C) results in approximately 70 % and 87 % reductions in rut depth, respectively. Extrapolating from these results, the temperature reductions achieved by the HAP system during critical loading hours would be expected to substantially lower the rate of rutting accumulation, offering a measurable extension of pavement service life under similar loading and climatic conditions.

## 3 MECHANICAL RESPONSE OF HAP SYSTEMS

In this section, the structural response of HAP is examined through an integrated approach combining laboratory experimentation and finite element (FE) modelling. The primary objective is to characterize the material properties of HAPs by evaluating their rutting resistance through performance testing. While material characterization of bituminous mixtures is typically performed at the laboratory scale, the relatively large size of embedded pipes in HAPs compared with standard specimen dimensions introduces significant scale effects that cannot be overlooked. To accurately capture these effects, larger specimen sizes must be employed, and conventional laboratory testing protocols require adaptation to accommodate larger samples, ensuring that the measured mechanical performance accurately reflects the influence of the embedded pipes in the heat exchanger layer.

### 3.1 *Materials and methods*

This section outlines the materials, sample preparation procedure, and testing methods. A dense asphalt mixture with a maximum aggregate size of 10 mm and a 50/70 penetration-grade bitumen was used. This mixture, commonly applied in Belgium for second-class roads, cycle paths, and parking areas, was selected for its suitability in HAP applications and its smaller aggregate size, which facilitates compaction around embedded pipes.

Slabs of asphalt were prepared in accordance with EN 12697-33 standard, with final dimensions of 600 mm × 400 mm with a thickness of 100 mm. The compaction of multiple layers, placement of a reinforcing grid, and embedded polyethylene (PE) collector pipes (outer diameter 20 mm, inner diameter 13 mm) presented challenges in achieving uniform compaction. To address this, a standardized procedure was implemented: asphalt mixtures were heated in an oven for approximately 4 hours to reach a uniform compaction temperature of 160 °C. On the first day, a 35 mm base layer was compacted, after which the asphalt was allowed to cool down and become stiff. The pipes and grid were then positioned, and the interface was bonded with a polymer-modified tack coat to improve adhesion and interface shear strength. The second layer, 65 mm thick, was placed over the first layer and compacted. Prepared slabs were subsequently cut into two replicate specimens for placement in the left and right wheel tracks testing machine.

Rutting tests were carried out using a wheel-tracking device in accordance with EN 12697-22, simulating heavy traffic loading. Tests were conducted at a controlled temperature (40°C - 50 °C depending on the experiment conditions) and a loading frequency of 1 Hz, applying a tire pressure of 600 kPa, equivalent to 5000 N rolling load. The specimens were subjected to 50000 load cycles to monitor permanent deformation progression. While the overall experimental program considered variations in embedment depth, pipe orientation, pavement temperature, and grid placement, the present study focuses on reference specimens tested at 50 °C due to ongoing laboratory investigations (Ghalandari et al., 2024).

### 3.2 *Structural finite element modelling of thermo-active roads*

This section outlines the methodology for developing a FE model of thermo-active roads, including the geometrical configuration, material modelling approach, and calibration of material properties based on laboratory testing (Figure 2). The primary objective of the FE framework is to simulate the rutting behavior of asphalt pavements incorporating embedded heat exchanger pipes, using a viscoelastic representation of the asphalt mixture.

The initial requirement for this modelling approach is the determination of the viscoelastic material properties for both the asphalt pavement and the heat exchanger layer. A two-dimensional FE model was developed using a linear elastic formulation with a creep subroutine to capture the time-dependent deformation behavior of asphalt. The time-hardening form of the creep power-law model was selected to represent viscoelastic deformation, while the collector pipes were modelled as linear elastic. The coefficients of the creep power-law model were calibrated using results from wheel-tracking tests on reference specimens without pipes. These calibrated parameters were subsequently implemented into the FE model to ensure consistency with experimental observations. The resulting viscoelastic parameters provide the basis for capturing the temperature-dependent mechanical behavior of asphalt in thermo-active road systems.

#### 3.2.1 *Creep power law*

The rutting performance of asphalt mixtures can be characterized using creep-based constitutive models, with the creep power-law formulation being one of the most widely employed approaches. This formulation is available in two principal forms: time-hardening and strain-hardening. In the present study, the nonlinear time-hardening variant, also referred to as the Norton–Bailey creep model, was adopted, as expressed in Equation (1):

$$\varepsilon_{vp} = A\sigma^{n}t^{m} \tag{1}$$

where $\varepsilon_{vp}$ $(-)$ is viscoplastic strain, $A$ $(s^{-1})$ is creep rate coefficient, $\sigma$ $(N/m^{2})$ is stress, $n$ $(-)$ and $m$ $(-)$ are stress and time exponents.

The model parameters $A$, $n$, and $m$ are obtained from a creep curve derived either from cyclic compression tests or from rutting performance tests. The time-hardening model does not capture the complete material response in all loading scenarios; however, it has proven effective in predicting viscoplastic deformation for sufficiently large numbers of load cycles. The principle has been successfully applied in previous research, where cyclic creep tests were used to establish creep curves for bituminous mixtures (Uzarowski, 2006).

The material properties required for the FE simulations were obtained from a combination of laboratory testing and reference data. The parameters of the creep power-law material model were determined based on the viscoplastic creep response of the asphalt pavement measured during wheel-tracking tests under controlled temperature and loading conditions. The recorded surface deformations, calculated as the average rut depth from specimens placed in the left and right wheel tracks of the testing machine, were converted into equivalent viscoplastic strains, which were then used to calibrate the time-hardening form of the creep model through regression analysis (Majidi Shad et al., 2022).

As the tests were performed under a single loading pressure, the stress exponent and creep rate coefficient appeared in the fitted equation as a combined constant. This limitation arises because a single stress level does not allow independent evaluation of the influence of stress magnitude and creep rate. To address this, calibration was conducted using an iterative linear regression procedure, followed by adjustments to optimize the agreement between model predictions and experimental data. The separation of the stress exponent and creep rate coefficient was achieved by assigning the stress exponent a value reported in the literature (Hojat Shamami & Khiavi, 2017), allowing the remaining parameter to be determined accordingly. The resulting calibrated viscoplastic and elastic material properties are presented in Table 1 and were subsequently implemented in the FE model for further analysis.

Table 1. Asphalt mixture and embedded pipe material properties and model coefficients (Ghalandari et al., 2021a; Al-Qadi Imad et al., 2009)

| Material properties | Symbol | Asphalt mixture (@50°C) | PE pipe | Unit |
|---|---|---|---|---|
| Young's modulus | *E* | *1090* | *650* | $MN/m^2$ |
| Poisson's ratio | *v* | *0.4* | *0.45* | - |
| Density | *ρ* | *2350* | *940* | $Kg/m^3$ |
| Creep rate coefficient | *A* | *7.17e-5* | - | $s^{-1}$ |
| Stress exponent | *n* | *0.5227* | - | - |
| Time exponent | *m* | *0.3271* | - | - |

### 3.3 *Comparison of FE model results and experimental rutting performance*

In this section, the rutting behavior of the asphalt pavement was evaluated, and the results of a comparative analysis between the measured performance and predictions obtained from FE modelling are discussed. Figure 2 shows the FE model of the rutting test featuring model geometry, mesh details, and boundary conditions. As the pavement structure was constructed entirely from the same asphalt mixture, the entire modelled domain was assigned a single material definition. The parameters derived from the laboratory calibration were therefore applied to the whole structure. The input elastic material properties, such as Young's modulus, Poisson's ratio, and density, were measured in the laboratory or obtained from the mixture information sheet provided by the contractor (Willemen Infra). Where specific values were unavailable, data were sourced from relevant literature (Al-Qadi Imad et al., 2009).

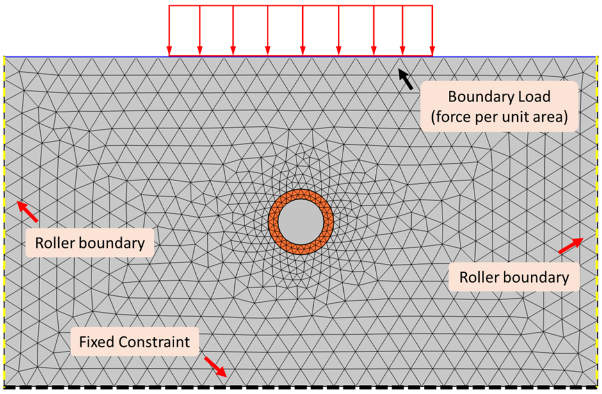

Figure 2. Two-dimensional finite element model of the HAP with boundary conditions

As illustrated in Figure 3, both the experimental measurements and FE predictions exhibit a progressive increase in rut depth over time, reflecting the continuous accumulation of permanent deformation under repeated loading. In the early phase of loading, the FE model exhibits slightly higher initial deformation rates compared to the experimental data, which may be attributed to the assumed constitutive behavior being more sensitive to initial loading than the actual material. As the loading progresses, the predicted rut depths align more closely with the experimental measurements, indicating that the calibrated creep parameters successfully capture the long-term deformation behavior. The comparison between the FE model predictions and experimental results shows strong agreement, with a mean absolute error (MAE) of 0.61 mm, a root mean square error (RMSE) of 0.70 mm, and a high coefficient of determination ($R^2 = 0.93$).

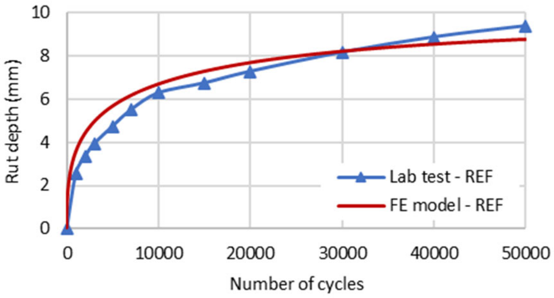

Figure 3. Comparison between measured and calculated rutting depth at the surface of the reference samples

A stage-wise evaluation highlights systematic variations in model accuracy. During the early phase of loading (0–5000 cycles), the FE model overpredicts rut depth, with MAE and RMSE values of 0.84 mm and 0.92 mm, respectively. The higher errors in these early stages could potentially be related to the predominance of densification and further compaction effects in the experimental samples that are not explicitly modelled in the adopted viscoplastic formulation in the current study. In the post-5000-cycle phase, the agreement improves significantly, with MAE and RMSE reduced to 0.44 mm and

0.48 mm, respectively. This improvement confirms that the calibrated FE model accurately captures the long-term viscoplastic response of the asphalt mixture once the initial compaction effects have stabilized.

To evaluate the transferability of the calibrated creep model, the material parameters obtained from the reference specimen were directly implemented in the FE model of the HAP configuration (Figure 2). The geometry was modified to include the embedded pipe, while the applied loading and temperature conditions replicated those of the HAP rutting test.

Figure 4 compares the predicted and measured rut depth evolution for the HAP specimen. The output results of the FE model successfully verify the overall rutting trend, with the final rut depth showing close agreement between experiment (9.99 mm) and simulation (9.82 mm). The comparison results are calculated as MAE = 0.45 mm, RMSE = 0.48 mm, with a high coefficient of determination ($R^2 = 0.97$), confirming the model's strong predictive capability. This validation confirms that the viscoplastic creep law derived from a conventional asphalt mixture can serve as a reliable modelling framework for rutting behavior in HAPs. The results demonstrate the applicability of the proposed modelling approach to both reference and modified pavement systems, while highlighting opportunities for refinement, particularly in capturing local thermo-mechanical interactions in the vicinity of the embedded pipes.

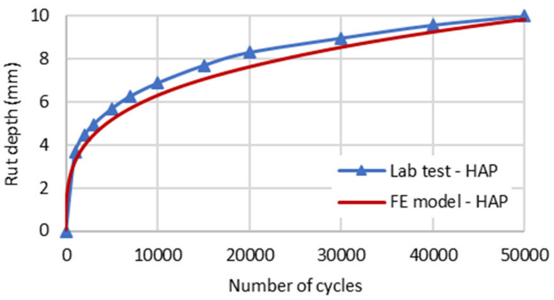

Figure 4. Comparison between measured and calculated rutting depth at the surface of the HAP samples

## 4 CONCLUSIONS

This study developed and validated a finite element framework for thermo-active road systems by integrating a structural model, calibrated with rutting performance tests, and long-term thermal data from field measurements.

Experimental results from the thermal response of the system demonstrated that activating hydronic asphalt pavements (HAPs) can reduce both surface and profile temperatures on average 8.73 °C and maximum up to 15.08 °C. Hence, By preventing excessive temperatures during peak traffic hours, the HAP system effectively minimizes the thermal component of rutting susceptibility, highlighting its potential to enhance long-term pavement performance.

Mechanical modelling, based on creep power-law calibration from wheel-tracking tests, showed close agreement with experimental results, with mean absolute errors of 0.61 mm for the reference and 0.45 mm for the HAP specimen. These results confirm the model's capability to replicate rutting behavior under realistic seasonal load–temperature conditions. The observed reductions in surface and profile temperatures provide direct input for thermo-mechanical analysis of thermo-active road systems, enabling the calibrated creep FE model to simulate rutting performance under realistic cooling conditions and seasonal load–temperature interactions.

## 5 ACKNOWLEDGEMENTS

The first author gratefully acknowledges the Research Foundation Flanders (FWO) for the postdoc fellowship [1223025N]. The authors kindly thank Willemen Infra for providing the asphalt mixtures used in this study.

## 6 REFERENCES

Al-Qadi Imad, L., Yoo Pyeong, J., Elseifi Mostafa, A. & Nelson, S. 2009. Creep Behavior of Hot-Mix Asphalt due to Heavy Vehicular Tire Loading. *Journal of Engineering Mechanics,* 135**,** 1265-1273.

Dakessian, L., Harfoushian, H., Habib, D., Chehab, G. R., Saad, G. & Srour, I. 2016. Finite element approach to assess the benefits of asphalt solar collectors. *Transportation Research Record,* 2575**,** 79-91.

Ghalandari, T., Baetens, R., Verhaert, I., Snm Nasir, D., Van Den Bergh, W. & Vuye, C. 2022. Thermal performance of a controllable pavement solar collector prototype with configuration flexibility. *Applied Energy,* 313**,** 118908.

Ghalandari, T., Ceulemans, D., Hasheminejad, N., Guldentops, G., Van Den Bergh, W., Verhaert, I. & Vuye, C. 2021a. A simplified model to assess the thermal performance of pavement solar collectors. *Applied Thermal Engineering,* 197**,** 117400.

Ghalandari, T., Hasheminejad, N., Van Den Bergh, W. & Vuye, C. 2021b. A critical review on large-scale research prototypes and actual projects of hydronic asphalt pavement systems. *Renewable Energy,* 177**,** 1421-1437.

Ghalandari, T., Hernando, D., Omranian, S., Van Den Bergh, W. & Vuye, C. 2024. Mechanical response assessment of pavement solar collectors. *Bituminous Mixtures and Pavements VIII.* CRC Press.

Ghalandari, T., Kia, A., Taborda, D. M. G., Van Den Bergh, W. & Vuye, C. 2023. Thermal performance optimisation of Pavement Solar Collectors using response surface methodology. *Renewable Energy*.

Hojat Shamami, V. & Khiavi, A. K. 2017. Effect of temperature on geosynthetic rutting performance in asphalt pavement. *Petroleum Science and Technology,* 35**,** 1104-1109.

Majidi Shad, M. M., Khabiri, M., Arabani, M. & Bahmani, H. 2022. 3D Finite Element Model for Recycled Asphalt Mixtures with High Percentages of Reclaimed Asphalt Pavement Rutting Simulation. *International Journal of Engineering,* 35**,** 1428-1439.

Majidifard, H., Jahangiri, B., Rath, P., Urra Contreras, L., Buttlar, W. G. & Alavi, A. H. 2021. Developing a prediction model for rutting depth of asphalt mixtures using gene expression programming. *Construction and Building Materials,* 267**,** 120543.

Mallick, R. B., Chen, B.-L. & Bhowmick, S. 2009a. Harvesting energy from asphalt pavements and reducing the heat island effect. 2**,** 214-228.

Mallick, R. B., Chen, B.-L. & Bhowmick, S. 2009b. Harvesting energy from asphalt pavements and reducing the heat island effect. *International Journal of Sustainable Engineering,* 2**,** 214-228.

Uzarowski, L. 2006. *The development of asphalt mix creep parameters and finite element modeling of asphalt rutting*, University of Waterloo Waterloo, Ontario, Canada.

Zhou, B., Pei, J., Richard Hughes, B., Snm Nasir, D., Vital, B., Pantua, C. a. J., Calautit, J. & Zhang, J. 2021. Structural response analysis of road pavement solar collector (RPSC) with serpentine heat pipes under validated temperature field. *Construction and Building Materials,* 268**,** 121110.

Zhu, X., Zhang, Q., Chen, L. & Du, Z. 2021. Mechanical response of hydronic asphalt pavement under temperature–vehicle coupled load: A finite element simulation and accelerated pavement testing study. *Construction and Building Materials,* 272**,** 121884.