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/ICSMGE2026-1074

Data-Driven Surrogate Modeling for Thermo-Active Road Design

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ABSTRACT: The traditional iterative design process for engineering problems involves evaluating the performance of initial solutions based on prior experience and expertise, comparing them against specified project criteria, and refining design variables to achieve the desired system performance. This cycle continues until a satisfactory solution is reached. However, for more complex problems, the computational demands of simulation modelling can become prohibitively high, especially in design optimization tasks. Surrogate models are machine learning-based representations of complex physics-driven simulations, enabling significantly faster computations. They provide a rapid and accurate means to evaluate responses across multiple design scenarios, making them invaluable for efficient design exploration and optimization. This paper investigates the application of surrogate modelling for the design and thermal performance assessment of thermo-active roads, with a particular focus on systems that integrate a heat exchange layer with embedded pipes in the asphalt pavement, known as Pavement Solar Collectors (PSCs). The surrogate model developed in this study is based on an artificial neural network (ANN) trained on a comprehensive database generated from finite element simulations. These simulations account for variations in geometric configurations and thermophysical properties of materials. The ANN model is designed to predict the outlet water temperature of PSC systems, which is then used to calculate their heat harvesting capacity. Following hyperparameter optimization to enhance the performance of the surrogate model, the proposed framework demonstrated its effectiveness in optimizing the design of a PSC system in a case study. This highlights the model's potential to simplify and improve the efficiency of the design process for thermo-active road systems.

KEYWORDS: Renewable energy, Pavement solar collector; Asphalt pavement, Surrogate modelling, Massive solar collectors.

1 INTRODUCTION

The growing global demand for energy, driven by rapid population growth, urbanization, and the urgent need for sustainable solutions to environmental challenges, has intensified the search for alternatives to fossil fuels. Among these alternatives, solar energy has emerged as a renewable and sustainable resource extensively studied across various engineering disciplines (Pei et al., 2019; Ahmad et al., 2019). Over the past two decades, research has increasingly focused on the development of thermo-active road systems, also referred to as Pavement Solar Collectors (PSCs), which are capable of capturing thermal energy from pavements exposed to substantial solar radiation.

Due to the dark color and high thermal capacity of bituminous asphalt, pavement temperatures at the surface can reach up to 70 °C in summer, corresponding to a potential thermal energy yield of up to 40 MJ/m² per day (Bobes-Jesus et al., 2013; Guldentops et al., 2016). This thermal energy can be harnessed by circulating a working fluid through embedded heat exchanger pipes in the pavement structure, exploiting the temperature gradient between the cooler fluid and the warmer asphalt. The recovered energy can be directly utilized for low-temperature applications such as domestic hot water supply, residential heating, and certain industrial processes, or alternatively, transferred to seasonal thermal storage systems (e.g., borehole fields or aquifers) for later use during winter (Mallick et al., 2012). This stored energy can then be reinjected into the pavement to prevent snow or ice accumulation, thereby enhancing road safety.

In addition to their thermal energy harvesting capabilities, PSC systems provide structural advantages by lowering pavement surface temperatures during summer. This temperature regulation has been shown to reduce thermally-induced pavement distress, including rutting, top-down cracking, and fatigue, thereby extending the service life of the pavement. In (Mallick et al., 2009), it was demonstrated that a 5 °C reduction in peak asphalt temperature could lead to an increase in pavement lifespan by approximately five years.

Recent studies have primarily focused on evaluating the thermal performance and feasibility of PSC systems through both laboratory-scale (Alonso-Estébanez et al., 2017) and field-scale (Johnsson & Adl-Zarrabi, 2020) experimental investigations. Complementary to these experimental approaches, numerical modeling approaches have been extensively employed to simulate PSC systems, conduct sensitivity analyses, and assess the impact of various design parameters. These include simplified thermal models, full-scale three-dimensional (3D) simulations, and hybrid modeling techniques (Masoumi et al., 2020) with a focus on optimizing accuracy while minimizing computational cost (Guldentops et al., 2016; Mirzanamadi et al., 2018).

While numerical simulations offer valuable insights into the thermal behavior and efficiency of PSC systems, their high computational demands often limit their use in long-term analyses or optimization studies involving numerous simulations. Direct coupling of optimization algorithms with full-scale simulations is frequently infeasible due to extended runtimes (Jiang et al., 2020). To address this limitation, surrogate modeling techniques are promising alternatives that approximate the input-output behavior of complex simulations at significantly reduced computational cost (Ferrero et al., 2023; Pirrone & Taborda, 2023). These surrogate models facilitate iterative design exploration, sensitivity analysis, and experimental parameter identification, making them particularly valuable for optimizing PSC systems (Jiang et al., 2020; Ghalandari et al., 2024).

Surrogate models in geotechnical engineering have been applied across diverse domains, including deep foundations, excavations, and energy geostructures. They have enabled efficient prediction of thermal integrity in concrete piles (Sánchez-Fernández et al., 2025b) and ground displacements around shafts in clay (Ruiz López et al., 2024), and have supported the application of the observational method to braced excavations (Ferrero et al., 2023). In energy geotechnics, surrogate models have been used to estimate thermal power output of thermo-active piles (Sánchez-Fernández et al., 2025a) and to support the back-analysis of monopile response using machine learning techniques for improved interpretation of offshore foundation behavior (Pirrone & Taborda, 2023).

This study aims to develop a surrogate modelling framework for predicting the thermal performance of thermo-active road systems using data generated from a validated finite element model. The surrogate model is applied for both forward performance prediction and inverse analysis of thermophysical material properties, demonstrating its efficiency and applicability for design optimization and field-scale implementation.

2 NUMERICAL MODELLING OF THERMO-ACTIVE ROADS

This section presents the finite element (FE) modelling framework developed to simulate the thermal behavior of thermo-active road systems, along with its validation using experimental data obtained from a full-scale PSC prototype. The FE model employed in this study builds upon a previously validated framework that demonstrated strong agreement with experimental measurements under various operating conditions (Ghalandari et al., 2023; Ghalandari et al., 2021).

The model's accuracy was assessed by comparing the simulated and measured temperatures of both the outlet fluid and the asphalt surface. Across several thermal experiments conducted under different climatic and operational scenarios, the mean absolute error (MAE) between simulated and measured outlet fluid temperatures averaged 0.51 °C. In addition, MAE was assessed for asphalt temperatures at multiple depths within the pavement structure. The average MAE values for asphalt temperatures remained below 1.0 °C, confirming the model's reliability in capturing the thermal behavior of the PSC system. These low MAE values collectively affirm the validity and accuracy of the FE framework in simulating the thermal response of thermo-active road systems (Ghalandari et al., 2023). To facilitate the development of a surrogate modelling framework, the geometry of the validated FE model was simplified while maintaining the same governing heat balance equations and boundary conditions used in prior work (Ghalandari et al., 2023). The modified FE model was then employed to generate a comprehensive dataset for surrogate model training, covering a wide range of geometrical configurations and parameter variations.

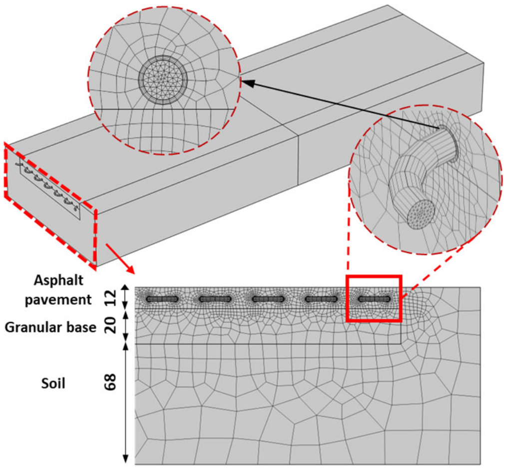

Figure 1. Simplified FE model for the PSC system with geometrical specifications and meshing details

For the surrogate modelling phase, the FE geometry was adapted to represent light-duty applications such as local roads and cycle paths. The model consisted of a 12 cm-thick asphalt layer over a 20 cm-thick compacted granular base. The thermo-active road section was modelled as a modular block with dimensions of 1.8 m × 8.35 m, corresponding to a net surface area of 15 m². These modular blocks can be replicated and connected to form extended road sections. Figure 1 illustrates the modified FE model geometry, meshing strategy, and the structural layout of the thermo-active road system.

3 SURROGATE MODEL DEVELOPMENT

This section outlines the development of a data-driven surrogate modelling framework designed to predict the thermal performance of thermo-active road systems. The approach is based on a validated FE model, which was simplified to efficiently generate synthetic data for surrogate model training, hyperparameter optimization, validation, and deployment. To ensure the practical applicability of the model outputs, design parameters were discretized into predefined intervals, reflecting realistic constraints associated with the design and construction of field-scale thermo-active roads. An I-optimal design of experiments (DoE) algorithm was employed to sample the design space efficiently, with the goal of minimizing the influence of random errors arising from uncontrolled variables in simulations or laboratory conditions. The ranges of input design variables used in the DoE sampling, along with the input weather data, are presented in Table 1.

Table 1. Range of input design factors for sampling and input weather data

Parameters (unit)	Min-Max.	Mean ± SD
Pipe spacing (cm)	10-30	20.43 ±8.5
Pipe depth (mm)	40-85	61.52 ±18.8
Pipe outer diameter (mm)	16-32	22.65 ±6.6
Supply temperature (°C)	10-16	12.83 ±2.4
Flow rate (l/min)	1-6	3.32 ±2.15
Thermal conductivity (W/mK)	1-2.5	1.74 ±0.62
Surface absorptivity (-)	0.65-0.95	0.80 ±0.13
Air temperature (°C)	8.68-31.72	18.82 ±4.95
Solar irradiation (W)	0-1010	185.54 ±250
Wind velocity (m/s)	0.02-8.67	1.27 ±1.05
Relative humidity (%)	20.09-99.5	70.62 ±19.6

A total of 46 design configurations, combining discrete numeric levels of selected parameters, were sampled using the I-optimal scheme. These configurations were then used to conduct transient FE simulations, resulting in a comprehensive dataset comprising over 30,000 data points obtained for a variety of time instants. This dataset, consisting of input features and corresponding output targets, served as the foundation for training an artificial neural network (ANN)-based surrogate model. The surrogate model employed a supervised learning framework with 11 input features grouped into four categories: (1) geometrical design parameters, (2) operational variables, (3) thermophysical properties of materials, and (4) weather conditions. The output layer consisted of a single node representing the outlet fluid temperature of the thermo-active road system. A summary of input and output parameters in ANN network is provided in Figure 2.

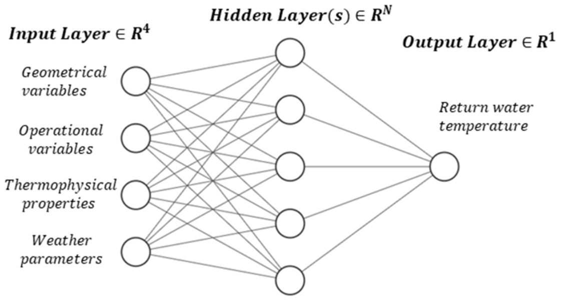

Figure 2. The ANN network architecture with input, hidden, and output layers

Prior to training, the data were standardized using a feature scaling method and randomly shuffled before being split into training and testing subsets in an 85:15 ratio. To prevent overfitting and underfitting, a holdout validation strategy was implemented using the 15% testing subset for model performance evaluation. Hyperparameter optimization was conducted using a grid search algorithm aimed at minimizing the mean squared error between predicted and actual output values. The set of hyperparameter combinations presented in Table 2 was systematically evaluated using a grid search, and the configuration achieving the highest performance (also reported in Table 2) was employed for all subsequent analyses.

Table 2. Hyperparameter search range and selected model parameters

Model hyperparameters	Search range	Selected model
Number layers	1, 2, 3	2
Layer(s) size	1 – 300	27-2
Regularization strength	3.5521E-10 – 3.5521	0.3146
Activation function	*Tanh, Sigmoid, ReLU*	*ReLU*

4 ASSESSMENT OF MODEL ACCURACY AND BACK-ANALYSIS USING FIELD-SCALE EXPERIMENTAL DATA

The developed surrogate model was applied to two primary scenarios: (1) the back-analysis of the thermophysical material parameters of the field-scale experimental setup, and (2) the assessment of the thermal response predicted by the surrogate model, which is compared with experimental data in order to evaluate the model's predictive capability.

For this purpose, experimental results obtained from a large-scale thermo-active road prototype at the University of Antwerp were utilized. The experiments were conducted over a five-day period, from 15 to 19 June 2021. The dataset consists of three experimental runs performed under consistent design, operational, and weather conditions, with the only variation being the inlet supply temperature (Ghalandari, 2025).

In the first experiment, the supply temperature was maintained at a constant value of 14.0 °C. In the remaining two experiments, the supply temperature varied due to system configuration, with average values of 19.9 °C and 23.3 °C, respectively. This controlled variation in supply temperature under otherwise identical boundary conditions provides an opportunity to assess the surrogate model's robustness across different operational scenarios. Figure 3 presents the outlet fluid temperatures recorded during the three experimental campaigns, illustrating the system's thermal response over the testing period. The comparison between the surrogate model predictions and the experimental measurements enables the evaluation of both the model's accuracy and its potential for inverse analysis to identify unknown or uncertain input parameters in field conditions.

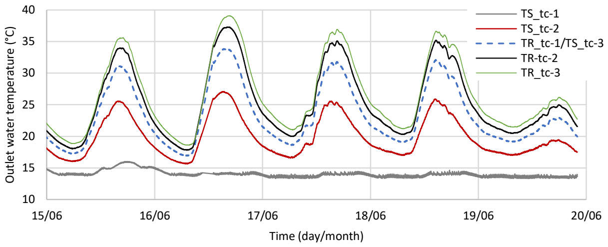

Figure 3. The supply (TS) and outlet water temperature (TR) for different test cases (tc) at hourly time steps

Given the close similarity in geometrical dimensions between the developed surrogate model and the experimental setup (both designed for application in cycle paths), the surrogate model was employed to identify the thermophysical properties of the asphalt pavement used in the field prototype. In this context, all geometrical, operational, and environmental parameters were known, enabling the inverse identification of unknown material properties (i.e., thermal conductivity and surface absorptivity of the asphalt material). The low computational cost of the surrogate model enabled efficient parameter identification using both classical iterative approaches and advanced optimization techniques. In this study, a particle swarm optimization (PSO) algorithm was implemented to minimize the objective function, defined as the absolute error between the experimental outlet temperatures and those predicted by the surrogate model (Ghalandari et al., 2024). Using this approach, the thermal conductivity and surface absorptivity of the asphalt pavement were estimated to be 1 (W/m.K) and 0.95 (-), respectively. Although asphalt surface emissivity is known to vary depending on surface conditions (e.g. dry, moist, or wet), it was assumed constant throughout the experimental period for the purpose of this analysis, and potential variations in emissivity were therefore neglected.

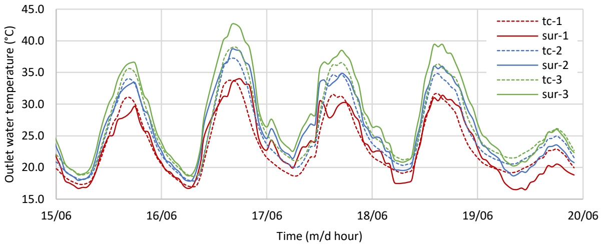

Figure 4. The experimental (dashed lines) and surrogate model data (continuous lines) of outlet water temperature for the validation period; with tc = test cases and sur = surrogate modelling approach, as red, blue, and green show lowest to highest supply temperatures.

Following the back-analysis of material properties, the surrogate model was applied to evaluate the thermal response of the large-scale field prototype. The predicted outlet temperatures from the ANN-based surrogate model were compared with the experimental measurements from the PSC system. Figure 4 presents the comparison of hourly outlet water temperatures for the three experimental sets, highlighting the agreement between surrogate model predictions and experimental observations.

The MAE values for the three experimental scenarios were 1.5 °C, 1.5 °C, and 1.8 °C, respectively, demonstrating a high level of predictive accuracy. Additionally, the correlation between the predicted and measured temperatures is shown in Figure 5, with coefficients of determination (R^2) of 0.85, 0.92, and 0.95 for the three respective tests. These results confirm the surrogate model’s capability to accurately predict the thermal response of the PSC under varying operational conditions. Consequently, the surrogate model has been shown to be a suitable tool for field-scale implementation that can be reliably used for design applications within or near the parameter space defined during model training. Moreover, the model demonstrates robustness against typical sources of uncertainty and variability inherent in field conditions.

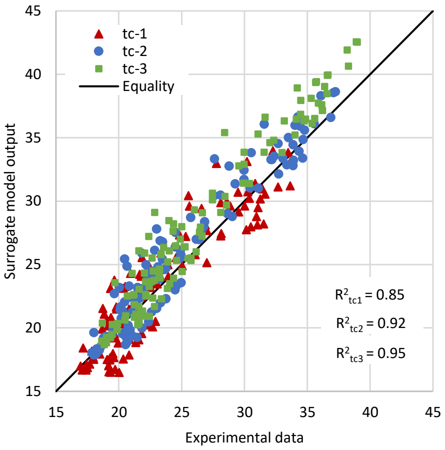

Figure 5. The experimental results vs. surrogate predictions of outlet temperature of the PSC for three test cases

5 CONCLUSIONS

This study presented the development and application of an artificial neural network (ANN)-based surrogate model to predict the thermal performance of thermo-active road systems. A validated finite element (FE) model was simplified to generate synthetic data for training the surrogate model, which incorporated a wide range of geometrical, operational, material, and environmental parameters. The resulting surrogate model demonstrated high accuracy, with low mean absolute error (MAE) values and strong agreement with the FE model outputs.

To demonstrate the applicability of the surrogate model for inverse modeling tasks, it was applied to the back-analysis of the thermophysical properties of asphalt pavement using an experimental dataset from a large-scale PSC prototype. By employing a particle swarm optimization algorithm, the surrogate model successfully identified key thermophysical properties of the asphalt, including thermal conductivity and surface absorptivity. Subsequent validation against field measurements yielded MAE values ranging from 1.5 to 1.8 °C and coefficients of determination (R^2) between 0.85 and 0.95, confirming the model's high predictive accuracy.

These findings indicate that the proposed surrogate modelling framework is not only computationally efficient but also robust and reliable for the design, analysis, and parameter identification of thermo-active roads. Furthermore, its demonstrated performance under real-world field conditions underscores its suitability for practical design applications within the trained parameter space, even when accounting for the inherent uncertainties of outdoor environments.

6 ACKNOWLEDGEMENTS

The first author gratefully acknowledges the Research Foundation Flanders (FWO) for the postdoc fellowship [1223025N].

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