

Article

Investigation of Roadway Anti-Icing Without Auxiliary Heat Using Hydronic Heated Pavements Coupled with Borehole Thermal Energy Storage

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Abstract

Roadway anti-icing requires low-carbon alternatives to chloride salts and electric heating. This study evaluated a seasonal thermal energy storage system that couples a geothermal hydronic heated pavement (HHPS-G) with borehole thermal energy storage (BTES), operated without auxiliary heat. A coupled transient HHPS-G–BTES model was developed and validated against independent experimental data. A continuous cycle was then simulated, consisting of three months of summer pavement heat harvesting and BTES, followed by three months of winter heat discharge. A parametric analysis varied borehole depth (10, 20, and 40 m) and number of units (1, 2, and 4). Results indicated that depth is consistently more effective than unit number. Deeper fields produced larger summer pavement surface cooling with less long-term drift and yielded more persistent winter anti-icing performance. The 40 m 4-unit case lowered the end-of-summer surface temperature by 3.8 °C relative to the no-operation case and kept the surface at or above 0 °C throughout winter. In contrast, the 10 m–1-unit case was near 0 °C by late winter. A depth-first BTES design, supplemented by spacing or edge placement to limit interference, showed practical potential for anti-icing without auxiliary heat.

Keywords: geothermal hydronic heated pavement (HHPS-G); borehole thermal energy storage (BTES); seasonal thermal energy storage system; roadway anti-icing



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1. Introduction

Winter roadway icing remains a persistent challenge for traffic safety and operating costs [1]. Conventional de-icing and snow-removal practices, most notably the application of calcium chloride, are widely used. However, calcium chloride can corrode structural components and promote oxidative aging (hardening) of pavement materials, potentially compromising embedded reinforcing steel [2]. In addition, runoff and infiltration of calcium chloride may contaminate soils and groundwater [3,4]. Accordingly, there is growing motivation to reduce reliance on de-icing salts while maintaining stable pavement surface temperatures by coupling operations to alternative heat sources.

One such candidate is thermal energy storage (TES), which harvests and stores naturally available heat (industrial waste, solar, and geothermal) for later use, potentially

displacing fossil-fuel heat supply and lowering energy use and cost [5–7]. TES can be classified by storage configuration into pit TES (PTES), tank TES (TTES), aquifer TES (ATES), and borehole TES (BTES) [8,9]. PTES and TTES can reach high storage temperatures but require substantial civil works and management of leakage and heat-loss, making them suited to large, high-temperature applications such as district heating [10–13]. ATES can be efficient but is constrained by hydrogeology and permitting [14,15]. BTES stores sensible heat in the ground via closed-loop borehole heat exchangers. While conduction-dominated transfer limits charging or discharging rates and very high storage temperatures, BTES offers broad site applicability and lower regulatory burden. Moreover, the relatively stable temperature of the shallow subsurface enables BTES to provide both heating and cooling services throughout the year [16–18]. Importantly, performance can be improved by optimizing design and operating (e.g., borehole depth, spacing, count, and layout; inlet and outlet fluid temperature and flow rate; grout and ground thermal properties; borehole thermal resistance) [19,20]. Long-term demonstrations coupled with solar harvesting have shown operational feasibility [21], and practical design guidance was analyzed [22].

Building on these characteristics, coupling BTES with a geothermal-source hydronic heated pavement (HHPS-G) has attracted increasing interest for roadway de-icing applications. In HHPS-G, closed-loop heat exchange pipes are embedded within or beneath the pavement, and a working fluid is circulated to raise or lower the surface temperature. During winter operation, fluid warmer than the ambient air is supplied to suppress the formation of snow and ice [23]. The de-icing and snow-removal performance of HHPS-G has been verified in small-scale experiments and numerical studies [24,25], and field deployments have also been reported [26,27]. Compared with practices such as calcium chloride application or electric heating cables, HHPS-G can markedly reduce energy use and carbon emissions [28]. Notably, HHPS-G can be used not only for winter heating but also for active summer cooling of the pavement, which helps mitigate pavement-induced heat-island effects and reduces excessive temperature rise that may otherwise lead to cracking and thermally induced stresses in asphalt or concrete structures [29,30]. Consequently, harvesting heat in summer, storing it in BTES, and reusing it for winter road de-icing can substantially lower operating costs for HHPS-G while simultaneously limiting summertime surface overheating.

Despite this promise, fully coupled, long-term analyses of HHPS-G with BTES operating without auxiliary heat remain scarce. Most prior work has stayed at a proof-of-concept stage, focusing on the basic feasibility of pavement heating and cooling [31,32]. More recently, performance analyses considering temperature and flow-rate control strategies for pavement heating have been reported [33], as well as parametric studies on pipe installation methods, flow rates, and pipe types embedded within the pavement [34,35]. However, system-level investigations that treat HHPS-G and BTES as a single coupled system, and simultaneously evaluate seasonal operating strategies, the influence of borehole geometry/layout/material properties, and de-icing performance under long-term thermal-storage behavior, are still limited. Although early case studies and numerical simulations of BTES-integrated roadway applications have been published, further quantitative evidence is needed to support field deployment [36,37].

To address this gap, a coupled transient model of HHPS-G and BTES was developed and validated. A series of numerical simulations was then conducted to quantify summer heat harvested into BTES according to borehole depth and number, and to assess whether stored heat alone (without auxiliary sources) could meet winter anti-icing demand under representative meteorological forcing. The findings support the practical potential of BTES-coupled pavements for anti-icing without auxiliary heat.

2. Development of Numerical Model

2.1. Overview of Modeling Approach

To develop a coupled thermal model for the HHPS-G–BTES system, COMSOL Multiphysics (Ver. 6.3, Stockholm, Sweden) was used to solve computational fluid dynamics (CFD) in the embedded pipes and transient heat conduction in the pavement, grout, boreholes, and surrounding ground. The problem was posed as a conjugate heat transfer analysis in which the fluid and solid subdomains were advanced simultaneously and exchanged heat across their common interfaces. Heat transfer from the circulating working fluid to the pipe wall and into adjacent media was governed by the conservation laws. The energy equation is given in Equation (1). The fluid phase satisfied continuity and energy conservation, while the solids satisfied the Fourier heat-conduction equation. Fluid–solid coupling enforced temperature continuity and normal heat flux continuity at the pipe wall.

$$\rho A C_p \frac{\partial T}{\partial t} + \rho A C_p u \nabla T = \nabla A k \nabla T + f_D \frac{\rho A}{2 d_h} |u|^3 + Q + Q_{wall} \quad (1)$$

where ρ is the density (kg/m^3), C_p is the heat capacity at constant pressure ($\text{J}/\text{kg}\cdot\text{K}$), T is the absolute temperature (K), t is the time (s), u is the translational velocity vector (m/s), k is the thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$), f_D is the Darcy friction factor, d_h is the hydraulic diameter (m), Q is the general internal heat source (W/m), and Q_{wall} is the heat exchange term with the surrounding media (W/m).

The embedded hydronic pipes were modeled as one-dimensional (1D) line elements using the Pipe Flow Module in COMSOL Multiphysics [38]. In this formulation, the pipe wall acts as the coupling interface between the 1D fluid domain and the surrounding three-dimensional (3D) solids (pavement and grout/ground). Continuity of temperature and normal heat flux is enforced at the 1D pipe wall. The computed wall heat transfer is then distributed to the adjacent 3D finite elements, while the 1D energy equation advances the in-pipe fluid temperature along the flow direction. This approach resolves conjugate heat transfer without explicitly meshing the pipe bore in 3D.

Heat exchange at the pavement–air boundary was imposed as a surface heat-flux boundary condition following Newton’s law of cooling (Equation (2)). Thus, no external airflow field was solved; instead, the time-varying ambient temperature and the validated convective coefficient, h , drive the boundary heat transfer.

$$q_c = h(T_{amb} - T) \quad (2)$$

where q_c is the convective heat flux (W/m^2), h is the Convection heat transfer coefficient ($\text{W}/\text{K}\cdot\text{m}^2$) and T_{amb} is the ambient air temperature (K).

2.2. Modeling of HHPS-G

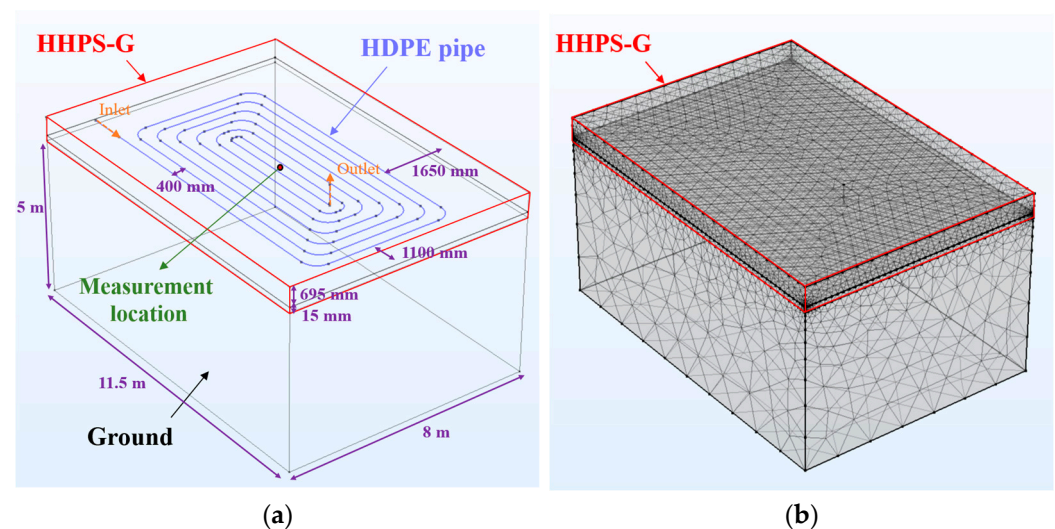
The heat exchange model for HHPS-G was validated against the concrete slab heating experiment reported by Lee et al. [39]. In that study, a 123 m-long pipe was embedded in the slab in a spiral layout, and water at a fixed inlet temperature of 25 °C was circulated continuously at a flow rate of 7.6 L/min to heat the slab. High-density polyethylene (HDPE) was used for the heat exchange pipe, owing to its corrosion resistance and installation-friendly flexibility. The installation layout of the slab and the embedded heat exchange pipes is detailed in the prior study [39], and a concise summary is provided in Table 1.

Table 1. Experimental conditions for HHPS-G slab heating.

Concrete Slab			Heat Exchange Pipe		
Area	Thickness	Installation depth	Length	Inner diameter	Outer diameter
49.5 m ²	710 mm	695 mm	123 m	24.6 mm	31.8 mm

An intermittent cycle of 8 h on/16 h off was applied each day. A thermocouple installed at a depth of 350 mm near the slab center recorded the temperature response to heating. In this work, the numerical model replicated the experimental configuration, boundary conditions, and operating schedule of Lee et al. [39]. The simulated temperature time series at the same instrumented location was then compared with the measured data to assess model fidelity.

Figure 1 presents the computational domain and the finite-element mesh used for the HHPS-G model. A mesh-sensitivity study was conducted to determine the minimum element size. The element size was systematically reduced, and the simulated instrumented-depth slab temperature was compared against the experimental data. As shown in Figure 2, convergence to the measurements occurred when the element edge length was reduced below approximately 0.205 m. Accordingly, the minimum element size was set to 0.205 m for the production simulations to balance accuracy and computational cost. The mesh consisted of approximately 79,000 tetrahedral elements. To resolve strong thermal gradients near the embedded pipes, local refinement was applied. For computational efficiency, the element size gradually increased toward the outer boundaries of the domain, with a maximum element size of 1140 mm. The minimum element quality satisfied the quality criterion of COMSOL Multiphysics, 0.01 [38].

**Figure 1.** Computational domain and finite-element mesh of HHPS-G model: (a) geometry; (b) mesh Configuration.

Material properties for each medium in the model were taken from prior experimental studies and are summarized in Table 2 [39]. The convective heat transfer coefficient, h , was determined by inverse analysis to best match the measured temperature time series at the thermocouple located at the mid-depth of the slab in the heating experiment. Consequently, a value of 10 W/K·m² was applied. Figure 3 compares the simulated temperature response from the developed model with the experimental measurements.

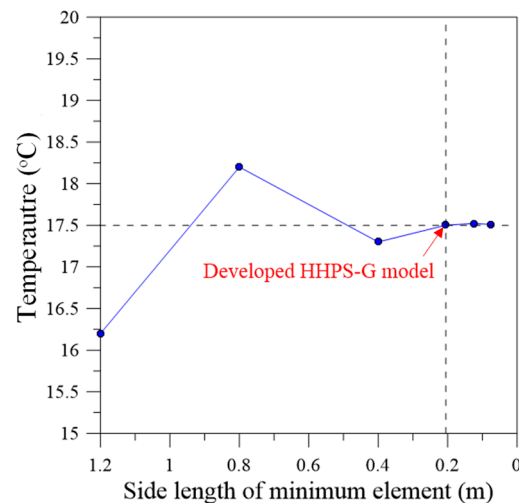


Figure 2. Mesh-sensitivity analysis results for slab instrumented-depth temperature.

Table 2. Thermophysical properties used in the HHPS-G model.

Materials	Density (kg/m ³)	Specific Heat Capacity (J/kg·K)	Thermal Conductivity (W/m·K)
Concrete	2300	880	2.0
Ground	2400	2300	1.3
Water	998	4182	0.6
HDPE pipe	955	525	0.4

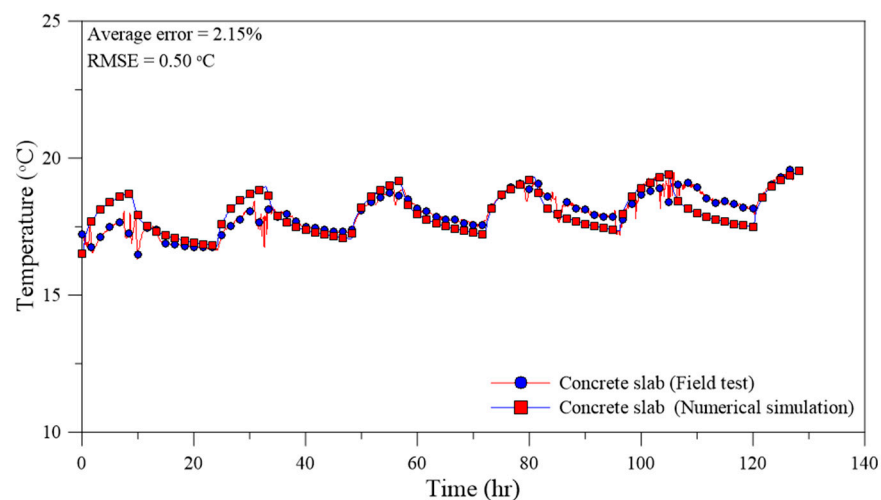


Figure 3. Comparison of experimental and simulated temperatures during slab heating.

Based on the validation, the average difference between the simulated and measured temperatures was 2.15%, and the root-mean-square error (RMSE) was 0.50 °C. Accordingly, the model is considered capable of reliably reproducing heat transfer in the HHPS-G and the resulting temperature response of the pipe-embedded slab.

2.3. Modeling of BTES

The BTES heat exchange and thermal storage model was validated against the borehole heating experiment reported by Park et al. [40]. In that study, a 1.5 m-diameter, 60 m-deep borehole was equipped with 103 m of W-shaped HDPE pipe. Water at a fixed inlet temperature of 30 °C was circulated at 2.56 L/min. Owing to construction constraints, the pipe was installed only down to 30 m and along a single borehole sidewall. Detailed

construction procedures are documented in the literature [40], and the principal parameters are summarized in Table 3.

Table 3. Experimental conditions for BTES heating.

Borehole (m)		Heat Exchange Pipe			
Diameter	Length	Installation depth	Length	Inner diameter	Outer diameter
1.5 m	60 m	Until 30 m	103 m	27.0 mm	35.0 mm

As in the HHPS-G test, an intermittent heating schedule of 8 h on/16 h off was applied. The borehole-wall temperature at a depth of 15 m was monitored. The numerical model replicated the experimental configuration and operating schedule, and the resulting borehole temperature response during heating was simulated to validate the BTES model. Figure 4 shows the computational domain and mesh. A mesh-sensitivity study was likewise performed for the BTES model. The element size was progressively reduced, and the simulated borehole-wall temperature response was compared with the measurement. As a result, convergence was achieved once the minimum element edge length was below approximately 0.1 mm (Figure 5). Accordingly, the minimum element size was set to 0.1 mm for the BTES simulations. The mesh comprised approximately 283,279 tetrahedral elements. To resolve strong gradients near the pipes while retaining efficiency, the element size was graded, with finer elements near the pipes and coarser toward the outer boundaries. The average element quality was 0.714.

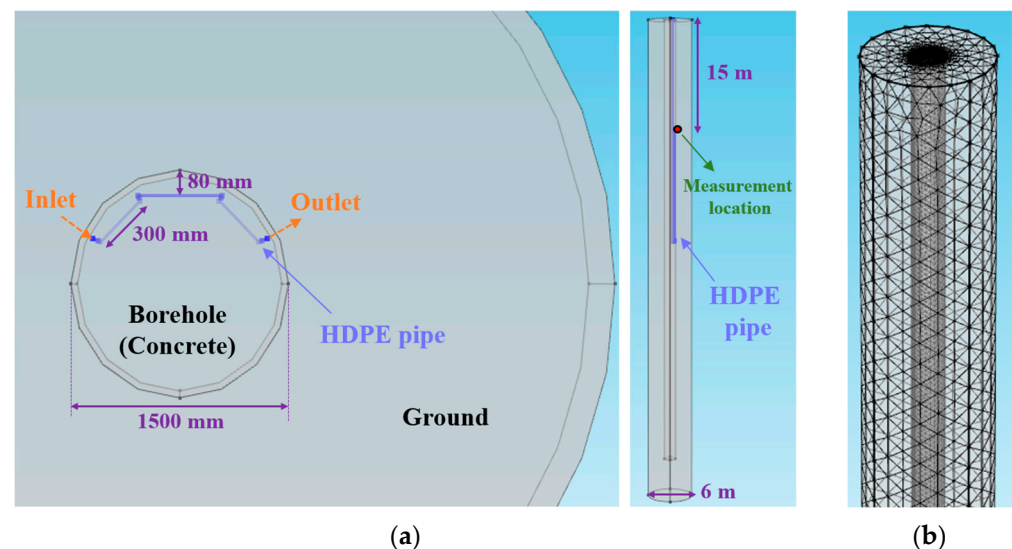


Figure 4. Computational domain and finite-element mesh of BTES model: (a) geometry; (b) mesh Configuration.

Thermophysical properties assigned to each medium were taken from prior experimental data, as summarized in Table 4. The properties of the heat exchange pipe and the working fluid (i.e., water) are identical to those used in the HHPS-G validation model and are listed in Table 2. A comparison of the simulated and measured temperatures is presented in Figure 6.

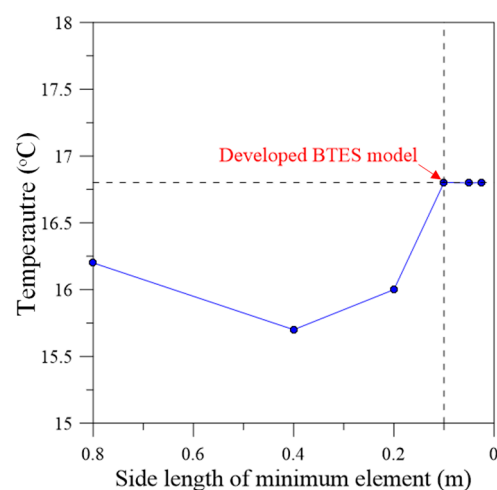


Figure 5. Mesh-sensitivity analysis results for borehole-wall temperature.

Table 4. Thermophysical properties used in the BTES model.

Materials	Density (kg/m ³)	Specific Heat Capacity (J/kg·K)	Thermal Conductivity (W/m·K)
Concrete	2162	800	2.1
Ground	1700	2500	1.7

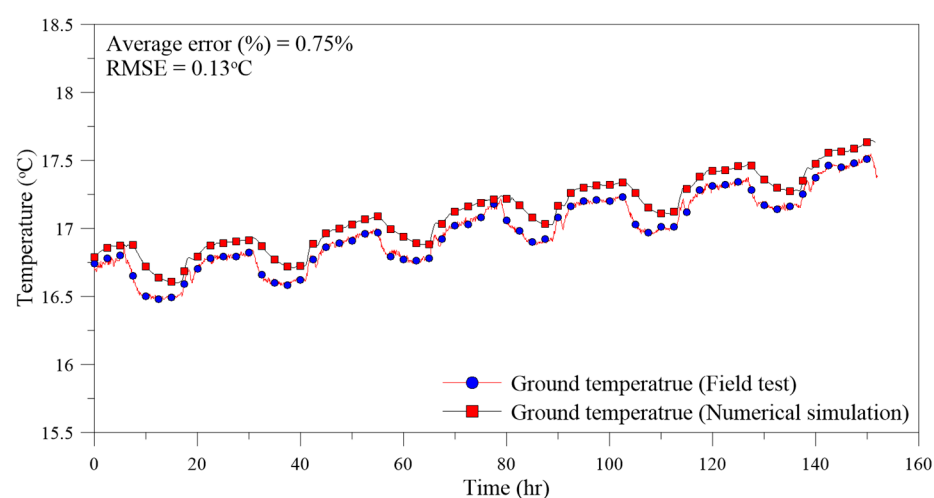


Figure 6. Comparison of experimental and simulated temperatures during borehole heating.

From the simulation results, the model reproduced the borehole-wall temperature evolution at 15 m depth with an average difference of 0.75% and an RMSE of 0.13 °C. Accordingly, the validated HHPS-G and BTES models were integrated to analyze heat harvesting through the pavement, seasonal subsurface heat storage via the borehole, and the resulting roadway de-icing performance. Table 5 summarizes the datasets used for validation, including geometry, operating conditions, and the corresponding model–data agreement metrics (average difference and RMSE).

Table 5. Summary of model conditions used for validation and corresponding results.

Ref.	System	Pipe Geometry	Flow Rate (L/min)	Inlet Temp. (°C)	Operation	Mean Error (%)	RMSE (°C)
Lee et al. [39]	HHPS-G	123 m HDPE pipe in a concrete slab	7.6	25	8 h on/16 h off	2.15	0.50
Park et al. [40]	BTES	103 m HDPE pipe in a 30 m-long borehole	2.56	30	8 h on/16 h off	0.75	0.13

3. Analysis of Pavement-Based Heat-Storage Performance According to BTES Installation Depth and Number

3.1. Overview of Parametric Analysis

In this section, an integrated numerical model was used to simulate the process by which heat harvested from the pavement by HHPS-G during summer is stored in BTES. It also quantified the effects of borehole installation depth and pipe unit count on harvesting and storage performance. Because instrumented datasets simultaneously measuring HHPS-G and BTES are not available, direct validation of the fully coupled system was not possible. Accordingly, an integrated numerical model, assembled from independently validated HHPS-G and BTES sub-models, was used to assess trends while all validated boundary conditions, mesh configurations, and operating parameters were held fixed. Only the borehole installation depth and pipe unit count were varied systematically to isolate their effects.

The pavement was idealized as a reinforced-concrete slab of 250 mm thickness with plan dimensions of 5.0 m × 5.5 m [37,41]. Below the slab, the stratigraphy comprised an insulation layer (70 mm), a basecourse (200 mm), and a subbase (250 mm) in sequence. The insulation layer was introduced to suppress downward heat losses and thereby strengthen heat transfer to the circulating working fluid. It was modeled as a generic insulation with thermal conductivity 0.018 W/m·K. HDPE heat exchange pipes were embedded at mid-depth of the slab in a serial zigzag layout, with a total embedded pipe length of 59 m.

After circulating through the pavement, the working fluid entered the ground and flowed through a single-U ground heat exchanger (GHE), forming a fully closed loop. No auxiliary heat source was used. Thus, the model represented a configuration in which the fluid absorbed heat from the pavement and then rejected it to the cooler ground for seasonal subsurface storage. Borehole depths of 10, 20, and 40 m and unit counts of 1, 2, and 4 were considered, yielding 9 cases in total. The total pipe length and other settings for each case are summarized in Table 6.

Table 6. BTES configurations considered in the parametric study.

Case	1	2	3	4	5	6	7	8	9
Borehole depth (m)	10			20			40		
Number of units	1	2	4	1	2	4	1	2	4
Total pipe length (m)	26.85	46.51	85.82	46.85	86.51	165.82	86.85	166.51	325.82

The ambient air temperature boundary condition was imposed on the pavement and ground surface using a periodic function that reproduces the observed summer diurnal cycle from prior work (Equation (3)) [18].

$$T_{amb, summer} = 26 - 7 \cos\left(\frac{2\pi}{86,400 t}\right) \quad (3)$$

Convective heat transfer was modeled using Equation (2), and the convective heat-transfer coefficient, h , was set to 10 W/K·m², as determined by inverse analysis during

HHPS-G model validation. Initial temperatures were set to 30 °C for the concrete pavement, basecourse, and subbase, and 15 °C for the subgrade (ground). Figure 7 shows the overall model, the summer and winter operating schematics, and the mesh configuration.

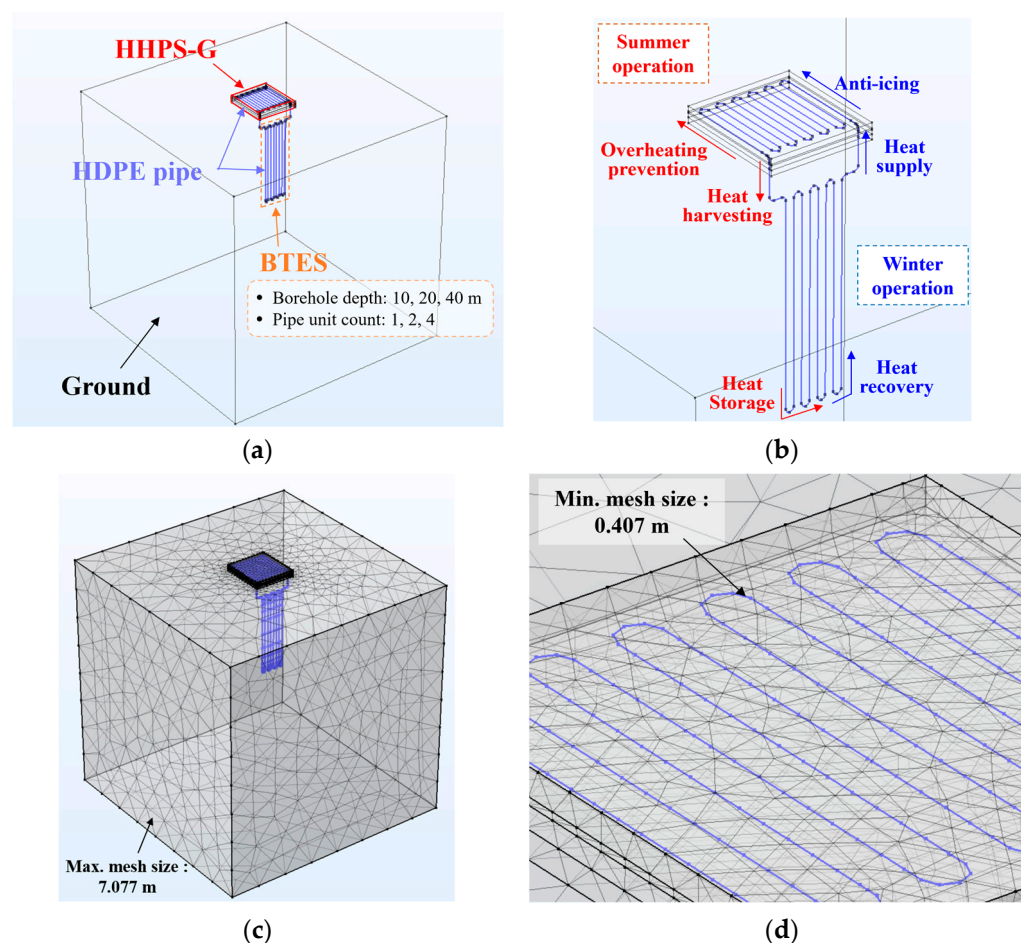


Figure 7. Overview and geometry of the coupled HHPS-G–BTES model: (a) overall computational domain and location of the HHPS-G–BTES system; (b) schematic of HHPS-G–BTES seasonal operation; (c) mesh configuration of entire model; (d) close-up of the minimum-size elements near pipes.

As in the validation models, the mesh was locally refined near the pipes to resolve steep thermal gradients. The minimum and maximum element edge lengths were 0.407 m and 7.077 m, respectively. The minimum element quality was 0.027, satisfying COMSOL's recommended threshold of 0.01 [39]. Material properties were taken from prior studies and are listed in Table 7 [42,43]. The working fluid was water. The system was operated continuously at 12 L/min for three months (2160 h), and the resulting behavior was simulated [29].

Table 7. Thermophysical properties used in HHPS-G–BTES numerical model.

Materials	Density (kg/m ³)	Specific Heat Capacity (J/kg·K)	Thermal Conductivity (W/m·K)
Concrete	2162	800	2.1
Thermal insulation layer	1000	750	0.018
Basecourse	2000	900	1.5
Subbase	1800	850	1.2
Ground	1800	850	1.2

3.2. Parametric Analysis Results

Figure 8 presents the pavement surface temperature time series over the three-month harvesting period. For each case, results were interpreted relative to a baseline without HHPS-G operation.

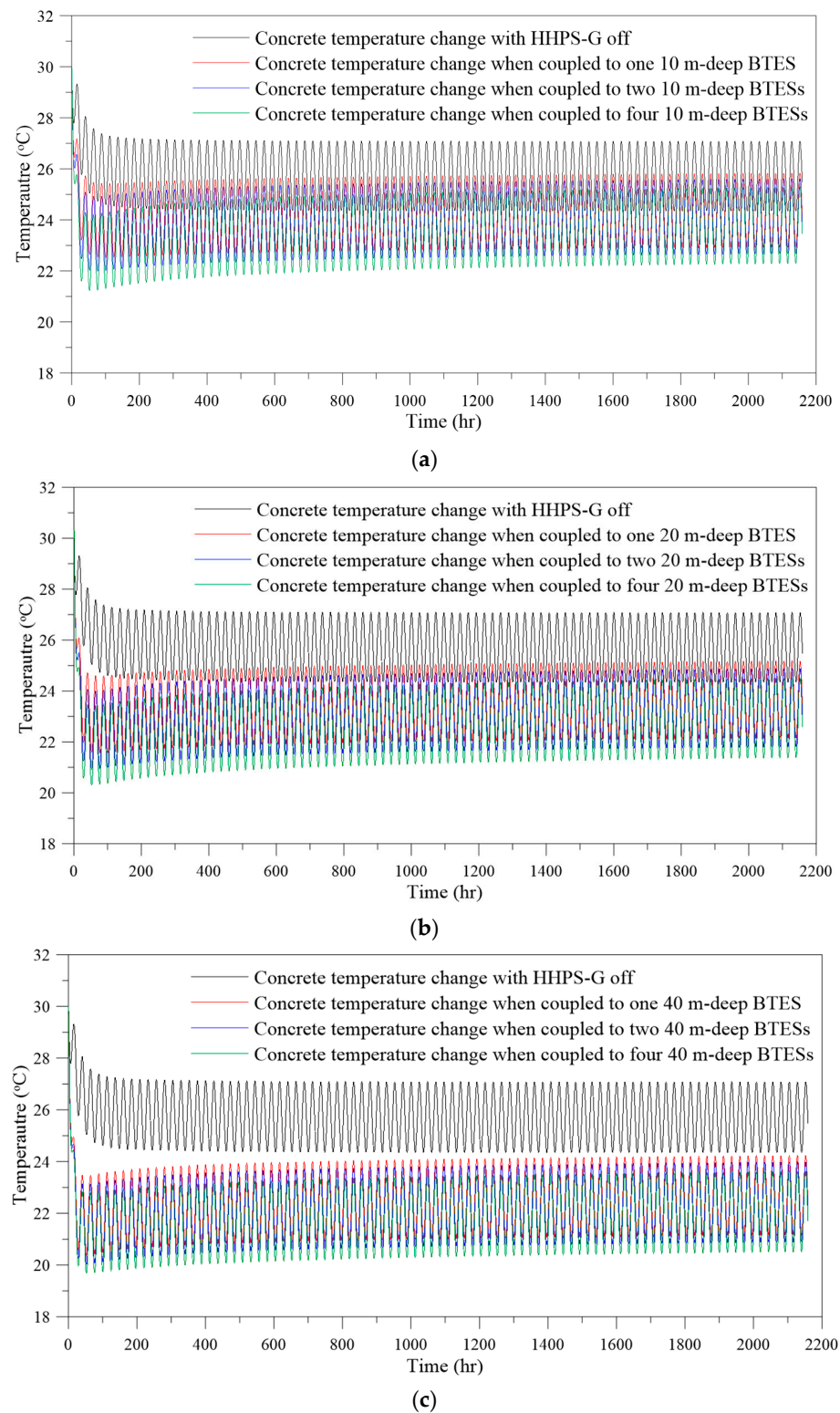


Figure 8. Pavement surface temperature during three months of summer heat harvesting for BTES depths of: (a) 10 m; (b) 20 m; (c) 40 m.

Compared with the baseline, coupling the pavement to BTES produced a clear cooling effect. The time-averaged surface temperature decreased, and the diurnal peaks were suppressed. Increasing the number of boreholes enhanced the cooling, yet the improvement showed diminishing returns. The expected cooling effect when increasing the number of boreholes from 1 to 2 was greater than when increasing from 2 to 4. This behavior was attributed to thermal interference among closely spaced boreholes, which reduced the marginal benefit of additional units. More importantly, increasing borehole depth was more effective for summer heat harvesting than merely adding units at shallow depth. As depth increased from 10 to 20 to 40 m, cooling improved, even at comparable total installed pipe length. Deeper fields, therefore, acted as a more persistent heat sink over the summer. These trends are summarized in Figure 9, which plots the surface temperature after three months versus total installed length for each depth.

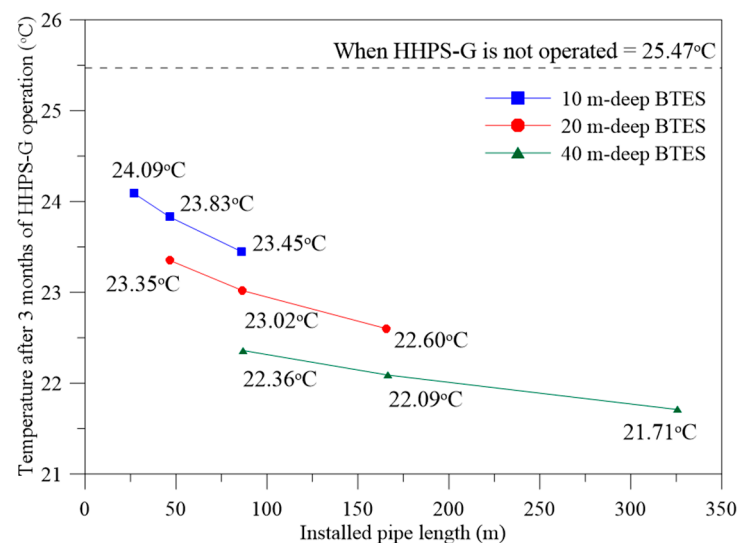


Figure 9. End-of-period pavement temperature as function of total BTES pipe length for depths of 10, 20, and 40 m.

At shallower BTES depths, the marginal reduction in pavement surface temperature gained by adding units was larger (i.e., the slope of the 10 m curve (blue in Figure 9) and was steeper than that of the 20 m and 40 m curves (red and green in Figure 9)). Nevertheless, increasing the installation depth rather than simply increasing the number of units yielded a proportionally greater overall benefit. This behavior arose because adding shallow BTES units intensified thermal interference among neighboring boreholes, which accelerated local ground warming. This reduced storage efficiency and made it harder to maintain a sufficiently low return temperature in the pavement loop. By contrast, increasing depth engaged a larger ground volume, thereby increasing storage capacity and enabling more effective heat storage and recovery.

To characterize the spatial evolution of the subsurface heat-storage zone, temperature time series were extracted at a depth of 5 m at lateral offsets from the pavement centerline of 0.0, 0.5, 1.0, 1.5, and 2.0 m (Figures 10–12). In addition, Figure 13 shows the radial ground-temperature profiles at 5 m depth after three months of summer operation, comparing 9 BTES configurations and illustrating a consistent lateral attenuation from the pavement centerline.

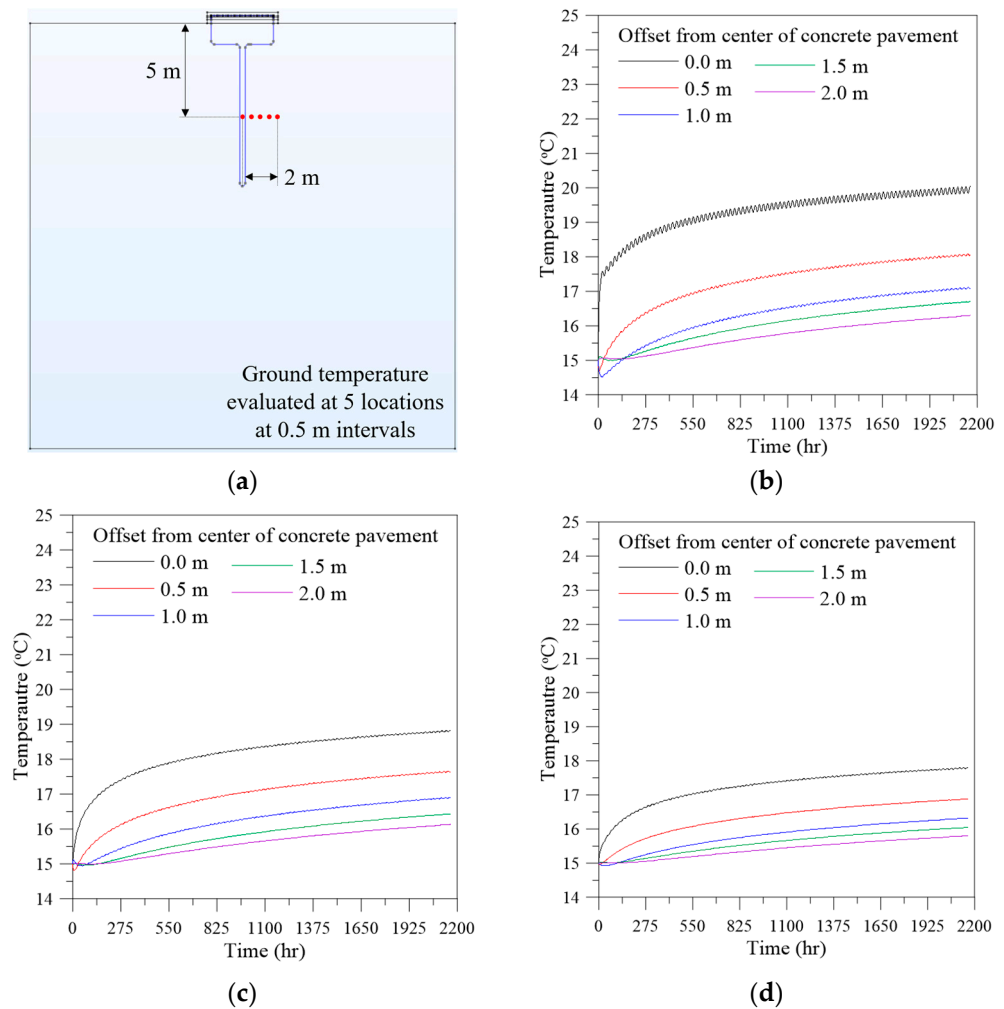


Figure 10. Subsurface temperature at 5 m depth during three months of summer heat harvesting using one BTES unit: (a) sampling layout with lateral offsets (0.0, 0.5, 1.0, 1.5, 2.0 m); (b) 10 m-deep BTES; (c) 20 m-deep BTES; (d) 40 m-deep BTES.

At all depths, the temperature rise peaked at the pavement centerline (0.0 m) and decayed monotonically with radial distance, exhibiting consistent spatial attenuation. Increasing the number of boreholes elevated temperatures at all offsets. In shallow fields, the rise became excessive, indicating local overheating and more substantial inter-borehole interference. By contrast, greater installation depth produced smaller ground-temperature increases for a given harvested heat. This indicates that shallow installation reduces effective storage volume, accelerates local warming, and ultimately lowers harvesting efficiency (Figure 13). The stored heat was inferred quantitatively from Equation (4).

$$Q_{stored} = \int_V \rho C \Delta T dV \quad (4)$$

where Q_{stored} denotes the stored sensible heat (MJ), ρ is the ground density (kg/m^3), C is the specific heat capacity ($\text{J}/\text{kg}\cdot\text{K}$), ΔT is the temperature rise relative to the initial state (K), and V is the control volume used to estimate storage (m^3).

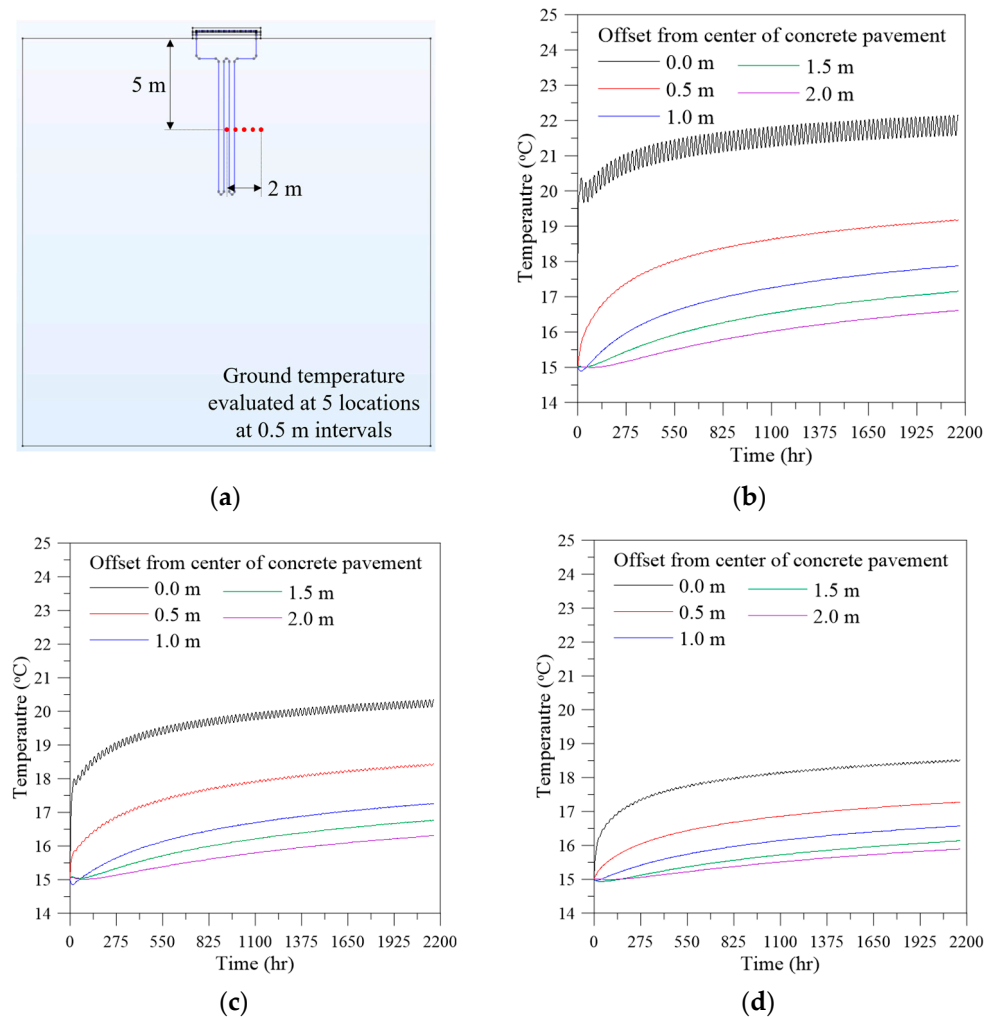


Figure 11. Subsurface temperature at 5 m depth during three months of summer heat harvesting using two BTES units: (a) sampling layout with lateral offsets (0.0, 0.5, 1.0, 1.5, 2.0 m); (b) 10 m-deep BTES; (c) 20 m-deep BTES; (d) 40 m-deep BTES.

For consistent case-to-case comparison, the analysis used a 2D section with a unit thickness of 1 m. The control volume for storage estimation was defined as a 4 m-wide band (± 2 m from the centerline) over the borehole depth. Using this outer-edge value yields a conservative lower bound because diffusive attenuation makes ΔT smallest at the band edge, whereas interior regions closer to the borehole exhibit larger rises. Consequently, the ΔT metric was calculated as the rise above the initial temperature (15 °C) sampled at 5 m depth and at the outermost lateral offset (2.0 m). The cross-sectional area was computed as (borehole depth) $\times$ 4 m, and the resulting estimates are summarized in Table 8.

Because Q_{stored} is evaluated directly from the simulated temperature field over V , previously incurred heat losses (e.g., surface convection or boundary leakage, etc.) are already reflected. Therefore, the estimated Q_{stored} represents the net sensible energy remaining in the control volume at the sampling time. Using ΔT at outer edge (2 m) further ensures a conservative lower bound relative to a volume average.

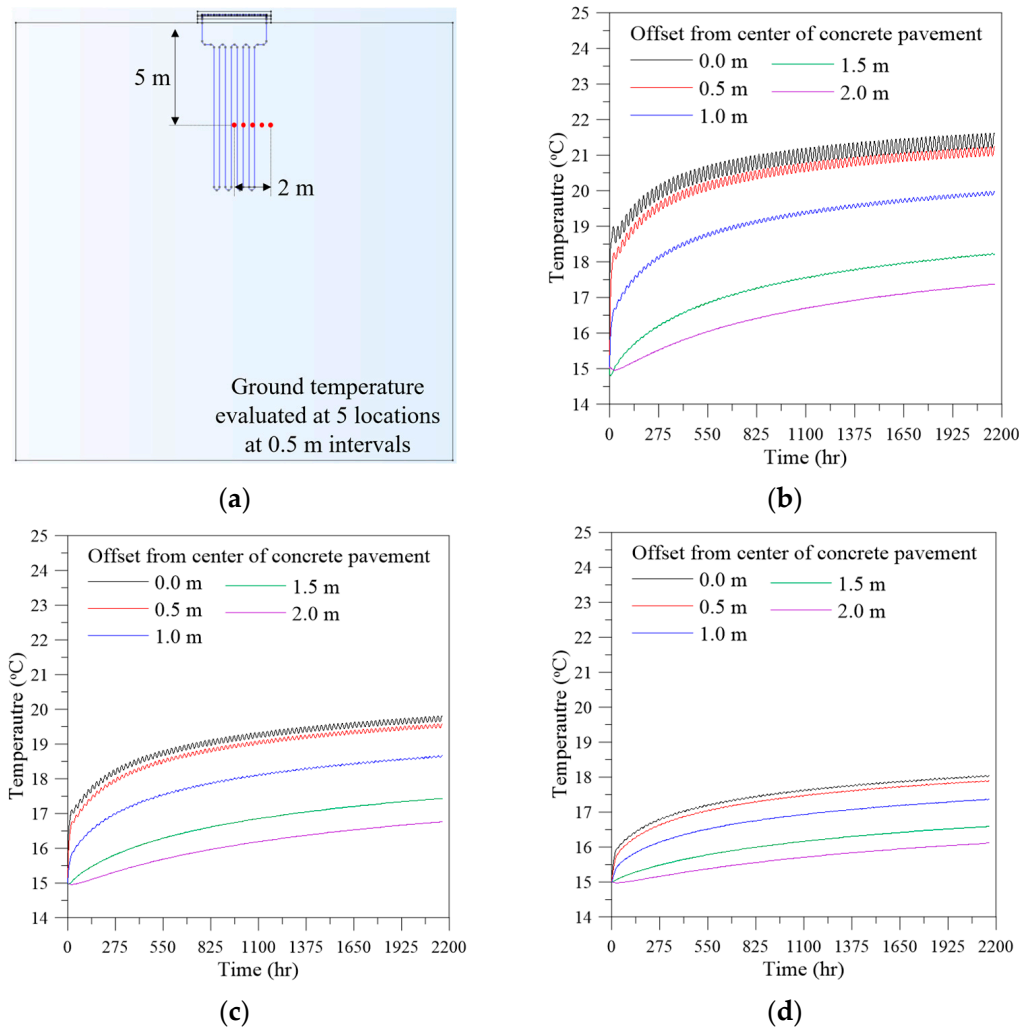


Figure 12. Subsurface temperature at 5 m depth during three months of summer heat harvesting using four BTES units: (a) sampling layout with lateral offsets (0.0, 0.5, 1.0, 1.5, 2.0 m); (b) 10 m-deep BTES; (c) 20 m-deep BTES; (d) 40 m-deep BTES.

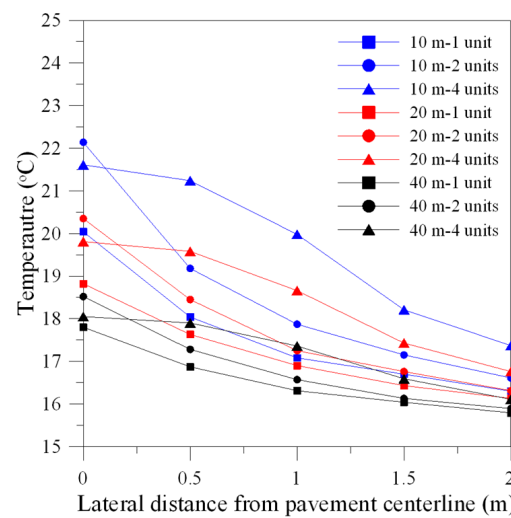


Figure 13. End-of-period radial ground temperature profiles at 5 m depth according to BTES installation depth and number of pipe units.

Table 8. Estimated stored heat based on outermost temperature rise (2 m offset).

Simulation Case		ΔT at 2 m Offset ($^{\circ}\text{C}$)	Q_{stored} (MJ)
10 m-deep BTES	1 unit	1.30	79.56
	2 units	1.61	98.53
	4 units	2.37	145.04
20 m-deep BTES	1 unit	1.13	138.31
	2 units	1.31	160.34
	4 units	1.76	215.42
40 m-deep BTES	1 unit	0.79	193.39
	2 units	0.89	217.87
	4 units	1.11	271.73

As shown in Table 8, at shallow installation depths, increasing the number of boreholes produced larger increases in the outer-edge temperature rise (ΔT at 2 m offset), whereas at greater depths, the same additions did not cause excessive warming. Using the same metric to estimate Q_{stored} , increasing depth yielded larger gains in Q_{stored} while simultaneously suppressing ground warming. This depth benefit reflects a larger effective storage volume (greater $\rho c V$), reduced sensitivity to surface forcing at depth, greater axial spreading that lowers local heat flux, and weaker overlap of thermal interference among boreholes.

Overall, increasing borehole depth is the most effective design lever for simultaneously improving pavement cooling and preserving subsurface heat storage. By contrast, simply adding units often provides limited improvements in both cooling and storage and may reduce economic efficiency. The drawback is most pronounced for multi-unit layouts at shallow depth, where inter-borehole thermal interference intensifies and substantially reduces the marginal benefit of additional units. Therefore, under typical spatial and budgetary constraints, depth should be prioritized, with adequate spacing and edge placement used as needed to mitigate interference.

4. Analysis of Anti-Icing Performance Using Heat Stored in BTES

In this section, additional simulations were conducted to assess whether winter anti-icing could be achieved without an auxiliary heat source, using only the heat harvested from the pavement in summer and stored in BTES. For comparison, two configurations were selected: the case that stored the least heat in summer (10 m–1 unit, case 1) and the case that stored the most (40 m–4 units, case 9). For both, the temperature field at the end of the three-month summer run was used unchanged as the initial condition for the winter analysis. The circulation loop was modeled as a fully closed circuit, as in summer, with no auxiliary heat input. The working fluid was operated continuously (24 h/day) with a flow rate of 12 L/min. Anti-icing performance was judged following prior studies; when the pavement surface temperature reached or exceeded 0°C , the system was considered to meet the minimum anti-icing requirement (a conservative criterion) [29,44]. The winter ambient temperature boundary condition reproduced the observed diurnal cycle using the periodic function, Equation (5) [18]. To reflect harsh, cold conditions, the mean temperature was set to -8°C .

$$T_{\text{amb,winter}} = -8 - 3\cos\left(\frac{2\pi}{86,400}t\right) \quad (5)$$

All other boundary and numerical settings were identical to those of the summer analysis. The results of the three-month winter operation are presented in Figure 14.

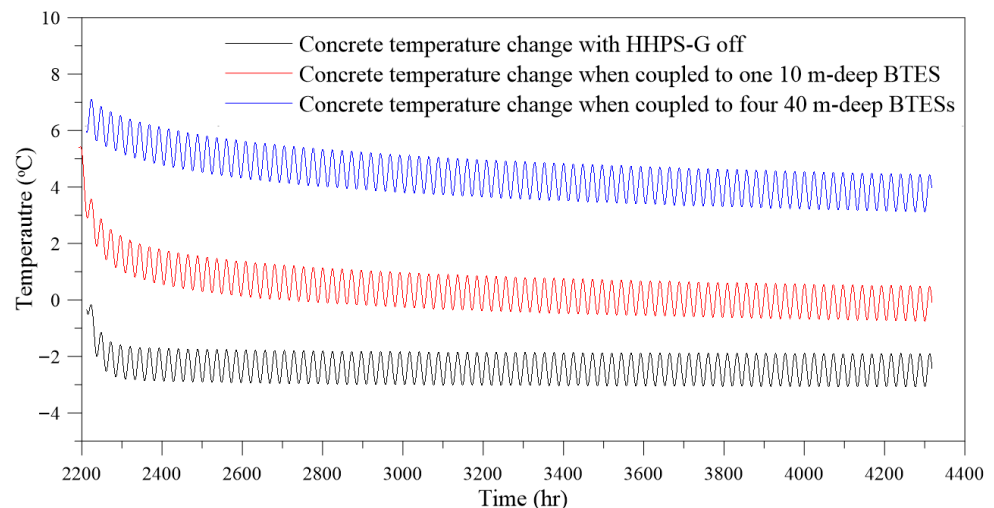


Figure 14. Pavement surface temperature during three months of winter operation using BTES-stored heat.

With HHPS-G off, the pavement surface temperature dropped rapidly into the sub-freezing range at the beginning of the run and remained frozen thereafter. In contrast, the 10 m–1 unit case started well above 0 °C and then declined gradually, remaining near 0 °C toward the end of the period. The 40 m–4 units case remained clearly above 0 °C throughout, exhibiting only a small long-term decline and thus indicating stable continuous operation. In short, deeper and multi-unit configurations provided a larger releasable heat inventory and a greater effective temperature head (ΔT), enabling robust anti-icing without auxiliary heat even under harsh cold conditions.

Figure 15 plots the temperature time series at a 5 m depth for the 10 m–1 unit and 40 m–4 units configurations at lateral offsets of 0.0–2.0 m (0.5 m intervals) from the pavement centerline.

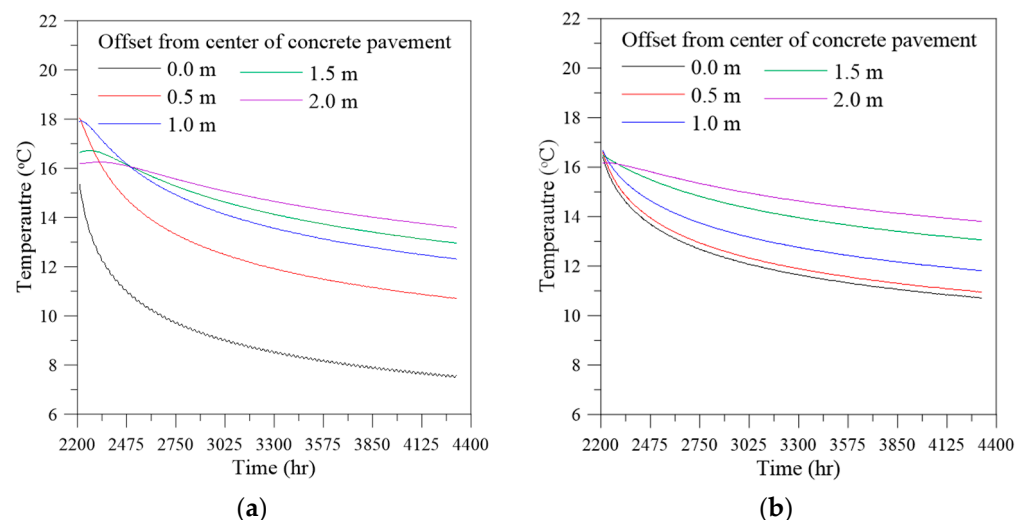


Figure 15. Subsurface temperature at 5 m depth during three months of winter operation using BTES-stored heat: (a) 10 m–1 unit; (b) 40 m–4 units.

For 10 m–1 unit, a steep early decline at the centerline (0.0 m) indicated rapid local depletion of stored heat near the pipe. As the radius increased, the decline became progressively weaker, leaving more residual heat toward the outer band. This behavior suggested that shallow, few-bore installations had a small effective storage volume, leading to rapid local depletion and a shrinking ΔT in the late stage of winter operation. For 40 m–4 units,

initial temperatures were higher, and the decay slopes were gentler at all offsets. In addition, the smaller radial temperature differences indicated more uniform discharge. Thus, increasing depth and pipe unit count formed a deeper and broader storage core, reduced the influence of surface boundary conditions, and favored long-term persistence.

Overall, the winter simulations indicated that adding units alone can improve initial performance for shallow fields but may cause late-season degradation due to local depletion and loss of ΔT . By contrast, increasing borehole depth improved both summer surface-temperature control and winter discharge stability, and therefore emerged as the primary variable to optimize. Note that the performance criterion used here was anti-icing, defined as maintaining the pavement surface temperature at or above 0 °C; explicit latent loads from snowfall and icing were not included. Future work should consider (1) de-icing scenarios that impose snowfall rates and latent heat of fusion, (2) the impact of operational control on performance and power use, and (3) multi-year operation to assess storage retention and boundary heat losses.

5. Discussion

This study demonstrated the feasibility and design trends of an auxiliary-free HHPS-G-BTES system using a coupled numerical model assembled from independently validated sub-models. Nevertheless, several limitations should be acknowledged. First, direct field validation of the fully coupled system under identical conditions is not yet available. Absolute performance, therefore, remains to be confirmed on scale. Second, the ground and pavement were modeled as homogeneous media with temperature-independent properties and no groundwater advection. In addition, moisture variations, freeze–thaw effects, and geologic heterogeneity were not represented. Third, ambient forcing was simplified to diurnal temperature functions with a fixed convective coefficient inferred during validation. Detailed wind/solar radiation dynamics and time-varying h were not included. Fourth, winter performance was judged by an anti-icing threshold (surface temperature at or above 0 °C) without explicit snowfall rates or latent heat loads. Finally, a closed energy-balance and a generalizable non-dimensional framework (e.g., Biot, Fourier, Reynolds, Nusselt, etc.) were not developed, which would require independently prescribed surface heat-transfer coefficients, layer-specific characteristic length scales, and controlled parameter studies.

Future efforts should conduct field experiments of coupled HHPS-G-BTES systems to establish absolute performance under real operating conditions and refine model calibration. The modeling framework should incorporate detailed meteorological drivers, including solar short-/long-wave radiation, wind, and precipitation, with time-varying convective and radiative exchanges at the surface. The physics should be extended to capture moisture transport, freeze–thaw processes, temperature-dependent properties, groundwater advection, and stratigraphic heterogeneity. In parallel, a compact non-dimensional framework should be developed to enable site-independent scaling. Finally, performance should be evaluated under explicit de-icing scenarios that include snowfall rates and icing latent-heat loads, with reliability assessed during extreme cold events. Collectively, these advances will close key realism gaps and provide the evidence base needed to translate BTES designs into robust, field-ready anti-icing solutions.

6. Conclusions

This study proposed a low-energy, low-carbon alternative to winter roadway de-icing by numerically assessing a seasonal system that couples an HHPS-G with BTES, operated without auxiliary heat. To this end, a coupled HHPS-G-BTES model was validated against independent experiments. A continuous annual cycle was then simulated, comprising three months of summer pavement heat harvesting and BTES, followed by three months

of winter heat discharge. The effects of the two key design variables, borehole depth and number of BTES, on summer heat harvesting, subsurface storage, and winter anti-icing performance were subsequently quantified. The significant findings are summarized as follows:

- (1) Model credibility was established through comparisons with prior experiments. The HHPS-G slab-heating replication and the BTES borehole-heating replication showed small errors, supporting the credibility of the component models used in the coupled analysis.
- (2) Using the validated methodology, a coupled HHPS-G–BTES model was developed. Increasing the depth of BTES consistently outperformed simply adding pipe units. Summer pavement cooling improved, and long-term drift diminished, while subsurface overheating was suppressed and total stored heat increased. Adding units at shallow depth yielded diminishing returns due to inter-borehole interference.
- (3) Under an anti-icing criterion (surface temperature at or above 0 °C), 40 m 4 units maintained a clear margin throughout winter, whereas 10 m–1 unit approached the threshold late in the period. Thus, a depth-first design is the most rational primary choice for robust auxiliary-free anti-icing.

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References

1. Kim, D.; Jung, S.; Yoon, S. Risk prediction for winter road accidents on expressways. *Appl. Sci.* **2021**, *11*, 9534. [\[CrossRef\]](#)
2. Kristufek, L. The Effect of De-icing Salts on the Chemistry of the Pore Solution in Cement Pastes and Their Influence on Rebar Corrosion. Master's Thesis, University of Waterloo, Waterloo, ON, Canada, 2020.
3. Fournier, I.B.; Lovejoy, C.; Vincent, W.F. Road salt versus urban snow effects on lake microbial communities. *Microorganisms* **2022**, *10*, 803. [\[CrossRef\]](#)
4. Hintz, W.D.; Fay, L.; Relyea, R.A. Road salts, human safety, and the rising salinity of our fresh waters. *Front. Ecol. Environ.* **2022**, *20*, 22–30. [\[CrossRef\]](#)
5. Guelpa, E.; Verda, V. Thermal energy storage in district heating and cooling systems: A review. *Appl. Energy* **2019**, *252*, 113474. [\[CrossRef\]](#)
6. Tian, Z.; Zhang, S.; Deng, J.; Fan, J.; Huang, J.; Kong, W.; Perers, B.; Furbo, S. Large-scale solar district heating plants in Danish smart thermal grid: Developments and recent trends. *Energy Convers. Manag.* **2019**, *189*, 67–80. [\[CrossRef\]](#)
7. Yang, T.; Liu, W.; Kramer, G.J.; Sun, Q. Seasonal thermal energy storage: A techno-economic literature review. *Renew. Sustain. Energy Rev.* **2021**, *139*, 1–22. [\[CrossRef\]](#)
8. Bott, C.; Dressel, I.; Bayer, P. State-of-technology review of water-based closed seasonal thermal energy storage systems. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109241. [\[CrossRef\]](#)
9. Mahon, H.; O'Connor, D.; Friedrich, D.; Hughes, B. A review of thermal energy storage technologies for seasonal loops. *Energy* **2022**, *239*, 122207. [\[CrossRef\]](#)
10. Villasmil, W.; Fischer, L.J.; Worlitschek, J. A review and evaluation of thermal insulation materials and methods for thermal energy storage systems. *Renew. Sustain. Energy Rev.* **2019**, *103*, 71–84. [\[CrossRef\]](#)
11. Chaib, M.; Benatallah, A.; Dahbi, A.; Hachemi, N.; Baira, F.; Boublia, A.; Ernst, B.; Alam, M.; Benguerba, Y. Long-term performance analysis of a large-scale photoVoltaic plant in extreme desert conditions. *Renew. Energy* **2024**, *236*, 121426. [\[CrossRef\]](#)

12. Schmidt, T.; Pauschinger, T.; Sørensen, P.A.; Snijders, A.; Djebbar, R.; Boulter, R.; Thornton, J. Design aspects for large-scale pit and aquifer thermal energy storage for district heating and cooling. *Energy Procedia* **2018**, *149*, 585–594. [\[CrossRef\]](#)
13. Dahash, A.; Ochs, F.; Janetti, M.B.; Streicher, W. Advances in seasonal thermal energy storage for solar district heating applications: A critical review on large-scale hot-water tank and pit thermal energy storage systems. *Appl. Energy* **2019**, *239*, 296–315. [\[CrossRef\]](#)
14. Fleuchaus, P.; Godschalk, B.; Stober, I.; Blum, P. Worldwide application of aquifer thermal energy storage—A review. *Renew. Sustain. Energy Rev.* **2018**, *94*, 861–876. [\[CrossRef\]](#)
15. Fleuchaus, P.; Schüppler, S.; Godschalk, B.; Bakema, G.; Blum, P. Performance analysis of aquifer thermal energy storage (ATES). *Renew. Energy* **2020**, *146*, 1536–1548. [\[CrossRef\]](#)
16. Shi, G.; Xi, S.; Wei, Z.; Li, C. Heat transfer performance of silicon carbide high thermal conductivity concrete energy piles. *Int. J. Green Energy* **2025**, *22*, 1185–1196. [\[CrossRef\]](#)
17. Park, S.; Lee, S.; Sung, C.; Choi, H. Applicability evaluation of cast-in-place energy piles based on two-year heating and cooling operation. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110906. [\[CrossRef\]](#)
18. Park, S.; Lee, D.; Lee, S.; Ahn, D.; Choi, H. Effect of thermal interference on energy pile considering various configurations of heat exchangers. *Energy Build.* **2019**, *199*, 381–401. [\[CrossRef\]](#)
19. Park, S.; Lee, S.; Oh, K.; Kim, D.; Choi, H. Engineering chart for thermal performance of cast-in-place energy pile considering thermal resistance. *Appl. Therm. Eng.* **2018**, *130*, 899–921. [\[CrossRef\]](#)
20. Park, S.; Lee, S.; Park, S.; Choi, H. Empirical formulas for borehole thermal resistance of parallel U-type cast-in-place energy pile. *Renew. Energy* **2022**, *197*, 211–227. [\[CrossRef\]](#)
21. Sibbitt, B.; McClenahan, D.; Djebbar, R.; Thornton, J.; Wong, B.; Carriere, J.; Kokko, J. The performance of a high solar fraction seasonal storage district heating system—five years of operation. *Energy Procedia* **2012**, *30*, 856–865. [\[CrossRef\]](#)
22. Gao, W.; Qadrdan, M.; Chaudry, M.; Wu, J. *Seasonal Storage of Heat in Boreholes*; Technical note; UK Energy Research Centre: London, UK, 2023.
23. Liu, X.; Rees, S.J.; Spitler, J.D. Modeling snow melting on heated pavement surfaces. Part I: Model development. *Appl. Therm. Eng.* **2007**, *27*, 1115–1124.
24. Zhao, W.; Chen, X.; Zhang, Y.; Su, W.; Xu, F.; Li, B. Deicing performances of a road unit driven by a hydronic heating system in severely cold regions of China. *Comput. Math. Appl.* **2021**, *81*, 838–850. [\[CrossRef\]](#)
25. Wu, X.; Ma, M.; Lu, J.; Su, L.; Yuan, X.; Chen, H.; Ishnazarov, O. A Passive Geothermal-Based Approach to Snow Melting Using Natural Circulation. *Heat Transf. Eng.* **2025**, *46*, 1–15. [\[CrossRef\]](#)
26. Tan, Y.Q.; Zhang, C.; Xu, H.; Tian, D. Snow melting and deicing characteristics and pavement performance of active deicing and snow melting pavement. *China J. Highw. Transp.* **2019**, *32*, 1–17.
27. Ziegler, W.; Nixon, C. *Geothermal System for Airport Pavement Snowmelt and Terminal Cooling* (No. DOT/FAA/TC-23/38); Department of Transportation, Federal Aviation Administration, William J. Hughes Technical Center: Washington, DC, USA, 2023.
28. Shen, W.; Ceylan, H.; Gopalakrishnan, K.; Kim, S.; Taylor, P.C.; Rehmann, C.R. Life cycle assessment of heated apron pavement system operations. *Transp. Res. Part D Transp. Environ.* **2016**, *48*, 316–331. [\[CrossRef\]](#)
29. Zhao, W.; Zhang, Y.; Li, L.; Su, W.; Li, B.; Fu, Z. Snow melting on the road surface driven by a geothermal system in the severely cold region of China. *Sustain. Energy Technol. Assess.* **2020**, *40*, 100781. [\[CrossRef\]](#)
30. Jaiswal, P.; Anupam, B.R.; Chandrappa, A.K.; Sahoo, U.C. Harvesting heat energy using geothermal and hydronic pavements for sustainable cities: A comprehensive review of an emerging idea. *Sustain. Cities Soc.* **2023**, *93*, 104539. [\[CrossRef\]](#)
31. Guldentops, G.; Nejad, A.M.; Vuye, C.; Rahbar, N. Performance of a pavement solar energy collector: Model development and validation. *Appl. Energy* **2016**, *163*, 180–189. [\[CrossRef\]](#)
32. Baumgaertel, S.; Schweighofer, J.A.; Rohn, J.; Luo, J. The performance of geothermal passive heating and cooling for asphalt and concrete pavement. *Dev. Built Environ.* **2021**, *7*, 100051. [\[CrossRef\]](#)
33. Ghalandari, T.; Baetens, R.; Verhaert, I.; Nasir, D.S.; Vuye, C. Thermal performance of a controllable pavement solar collector prototype with configuration flexibility. *Appl. Energy* **2022**, *313*, 118908. [\[CrossRef\]](#)
34. Lim, H.; Lee, S.; Lee, J. Effective snow removal devices for road pavement using geothermal heat pipe. *Appl. Therm. Eng.* **2025**, *265*, 125624. [\[CrossRef\]](#)
35. Zhao, W.; Su, W.; Li, L.; Zhang, Y.; Li, B. Optimization design of the road unit in a hydronic snow melting system with porous snow. *J. Therm. Anal. Calorim.* **2020**, *141*, 1509–1517. [\[CrossRef\]](#)
36. Johnsson, J. *Winter Road Maintenance Using Renewable Thermal*. Master's Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2017.
37. Mirzanamadi, R.; Hagentoft, C.E.; Johansson, P. Numerical investigation of harvesting solar energy and anti-icing road surfaces using a hydronic heating pavement and borehole thermal energy storage. *Energies* **2018**, *11*, 3443. [\[CrossRef\]](#)
38. COMSOL Multiphysics. *COMSOL Multiphysics Heat Transfer Module User's Guide 5.5*; COMSOL Inc.: Burlington, MA, USA, 2019.
39. Lee, S.; Park, S.; Han, T.H.; Won, J.; Choi, H. Applicability evaluation of energy slabs installed in an underground parking lot. *Sustainability* **2023**, *15*, 2973. [\[CrossRef\]](#)

40. Park, S.; Lee, D.; Lee, S.; Chauchois, A.; Choi, H. Experimental and numerical analysis on thermal performance of large-diameter cast-in-place energy pile constructed in soft ground. *Energy* **2017**, *118*, 297–311. [[CrossRef](#)]
41. Côté, J.; Konrad, J.M. Thermal conductivity of base-course materials. *Can. Geotech. J.* **2005**, *42*, 61–78. [[CrossRef](#)]
42. Lee, J.H.; Kim, D.H.; Moon, K.H.; Falchetto, A.C.; Kim, J.C.; Jeong, J.H. Development of representative section selection method for large-scale concrete pavement remodeling project based on trial and error correction approach. *Int. J. Pavement Res. Technol.* **2019**, *12*, 17–25. [[CrossRef](#)]
43. Choi, H.J.; Kim, S.; Kim, Y.; Won, J. Predicting frost depth of soils in south Korea using machine learning techniques. *Sustainability* **2022**, *14*, 9767. [[CrossRef](#)]
44. Adl-Zarrabi, B.; Gehlin, S.; Cetin, A.; Staudacher, L. Ground source de-icing and snow melting systems for infrastructure. *Transp. Res. Procedia* **2023**, *72*, 1621–1628. [[CrossRef](#)]

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